Radon fast detection and environmental monitoring with a portable wireless system

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Abstract—The World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) have already classified radon as a human carcinogen and have demonstrated a correlation between environmental radon concentration and lung cancer risk. Radon dosimetry supplies valuable information about radioactive health risks in indoor environments. Dose measurements are traditionally based on laboratory analysis of alpha-ray traces in ionization chambers exposed to environmental air or passive detectors based on polycarbonate material. The main goal of this work is to develop a portable and small system with real-time indoor Radon detection capabilities. The developed system, with embedded processing and wireless communication capabilities, is based on a Zinc-Sulfat screen coupled to a Silicon Photomultiplier (SiPM) transducer, low cost read-out electronics and system ventilation. The device is able to monitor environmental data, so it could have multiple uses in research and industrial applications.

Index Terms—Radon; SiPM; alpha-ray detector; portable; wireless;

I. INTRODUCTION

Radon ($^{222}$Rn) is a colourless, odourless, tasteless radioactive gas that comes from granitic or shale related areas in the ground. It can often be sourced by granite floors materials or even from construction materials, thus polluting indoor air [1]. Radon was identified as a human lung carcinogen in 1986 by the WHO (World Health Organization) [2]. According to this organization, radon gas is by far the most important source of ionizing radiation among those that are of natural origin. Most of the inhaled radon gas is immediately exhaled, however, if decay occurs in the lungs, the resulting solid radioactive particles can settle onto bronchial epithelial cells causing DNA damage. This gas constitutes the second cause of lung cancer deaths. Indoor Radon detection can be used to assess the radioactive health risk in a given place [3]. Outdoor detection can be useful in mining to detect concentrations of uranium as well as for earthquakes prediction studies [4,5]. In all these applications, portability is a key feature of the detector. Various radon detection apparatuses have been proposed. The classical method consists in a so-called “grab sampling”. This technique exploits capturing different samples obtained by filtering air at a test site through a charcoal filter at different time slots. The samples are then analyzed in a laboratory by a gamma spectrometer. Continuous radon detection is nowadays performed by in-field alpha spectroscopy or passive closed-end cup devices based on polycarbonate detector material, such as PACD or CR-39. Sensing elements are sealed ionization chambers or surface barrier semiconductor diodes with an active surface sufficiently thin that alpha particles impinging on the surface will pass the surface barrier and deposit their energy in the depletion region of the diode. Carefully manufactured diffusion junction diodes have also been proposed [5]. Other devices exploit internal signal amplification based on the bipolar transistor (BJT) effect that can be efficiently used for alpha-ray detection. For these detectors, difficulties with low signal levels, electrical noise and disturbances lead to misinterpretation of the detected signal [6]. Besides this, the main disadvantage is that reliable Radon concentration values are given after days or weeks. It is now an established fact that high radon concentration in the houses may pose a significant risk of lung cancer to the people living there. Studies from all over the world show that a well-planned and systematic measurement of indoor radon concentration is necessary to calculate the actual dose received upon indoor radon concentration exposure. In recent years, several studies have been made in relation to the effect of different parameters on the detected level of indoor radon. In fact, the radon concentration and its decay products in dwellings show large temporal and local fluctuations due to the temperature, pressure, humidity, building material, ventilation condition, wind speed, etc [7]. In this paper we propose a portable instrument for real-time radon detection and environmental data monitoring, based on a SiPM detector and low-cost readout electronics.

II. SYSTEM ARCHITECTURE

The presented platform aims to provide reliable Radon indoor concentration in a few hours. The prototype is designed with small dimensions in order to be portable and it is composed of two parts: one is the ventilation system and the other is the electronic board. The processed data are transmitted via Bluetooth to a mobile device, providing a real-time feedback to the user.
A. Alpha detector

The radiation detection via scintillation light involves very low levels of light. Thus, the photosensor has to be either very efficient, or provide internal gain, so that the charge photogenerated is amplified to obtain high signal-to-noise ratio (SNR). Photodiodes (PDs) have high quantum efficiency but they have some shortcoming such as no- to modest gain, so that the instrumentation design is complex due to poor SNR. Photomultiplier tubes (PMTs) have very high gain, about $10^6$, but they are bulky, fragile and require high voltages in the order of kilovolts. In the late 90s a new device was envisioned that could offer the high gain of PMTs and some of the advantages of Silicon photodetectors. Such devices are known as Silicon photomultipliers (SiPMs in short). These devices are based on small (tens of $\mu$m$^2$-sized) elementary cells that respond to a single light photon through an avalanche effect in a very similar way to Geiger-Mueller counters. If several such elementary cells are constructed on a larger area, they are able to detect the energy deposited in the scintillator in a proportional way. Each cell is practically a photodiode and a quench resistor in series to limit the discharge current. The photodiode operates a few volts above its breakdown voltage so that electrical breakdown occurs if a photoelectron is generated within the active volume. In order to be sensitive to successive photons every avalanche breakdown is interrupted by the built-in quench resistor. Relevant SiPM properties are low operating voltage (usually lower than 100 V), ruggedness, insensitivity to magnetic fields as well as compact dimensions [8]. For this application we chose a scalable SiPM (ArraySM-4) from SensL coupled with a ZnS screen (a scintillator sensitive to alpha particles) [9]. This sensor is based upon 4x4 arrangement of 3 mm SiPM pixels, which are mounted in a low profile ceramic package, coupled with ZnS(Ag) scintillator (BC-630). The scintillator has a 250 $\mu$m Mylar transparent window. This thickness is optimized for maximum efficiency in collecting alphas with 5.6 MeV energy and below.

B. Readout electronic

Figure 1 reports the block diagram of the readout Analog-Front-End, whose main goal is to collect, amplify and filter the charge signal produced by the SiPM, upon interaction with an alpha particle. The input stage is a common base with local feedback to lower the overall input impedance. Similar circuits have been presented and discussed in the literature [10]. Having a low first stage input impedance is important due to the SiPM high capacitance ($\sim 13.6$ nF for the whole sensor): just a few ohm will severely limit the readout bandwidth, decrease the amount of charge collected and hinder overall performance. The 16 pixels of the SiPM array are connected in parallel mode at the single input channel. Figure 2 shows the transfer function of the first circuit stage. The second stage is a charge preamplifier used for integrating the charge signal and converting it in a voltage signal with an amplitude proportional to the charge released in the detector. The cutoff frequency of the charge preamplifier is 8 kHz. The third stage is a shaper, designed in order to optimize the SNR ratio. Finally, a discriminator detects the signal pulses exceeding a preset threshold.

C. System ventilation

The design of the air sampling system is strongly linked to the desired system resolution and measurement time. Typical limits are often dictated by the effects Radon has with respect to a given target. The target could be effects on human body or airborne contamination measurements. For example, the United States Environmental Protection Agency (EPA) sets a limit of 4 pCi/l in residential dwellings before a human health alarm is raised and mitigation has to be considered. For simplicity, and given our specific application, we adopted 1/10th the EPA limit as minimum detectable activity for our system. If we assume 1 liter of air contains 0.4 pCi of alpha activity, varying air flows in a constant volume, and 100% detection efficiency (i.e. all alphas present in a volume are detected by some means) table I, can be constructed correlating the activity in the control volume vs. the air flow within the volume.

This means, for example, that at 1 l/s we expect to see about 1.5 decays in 100 seconds if the air activity is constant at 0.4 pCi/l. In an ideal world, after 100 seconds we would know beyond any doubt what the activity was. In reality, one has to account for the fact that the processes are random in nature and there is a degree of associated uncertainty. For N random samples, such uncertainty can be expressed as $\sqrt{N}$, thus, we can define a signal-to-noise ratio of our measurement as $\text{signal/noise} = N/\sqrt{N}$. By plotting the SNR as a function of...
Table I

<table>
<thead>
<tr>
<th>Liter/sec</th>
<th>Total decays/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.00148</td>
</tr>
<tr>
<td>0.2</td>
<td>0.00296</td>
</tr>
<tr>
<td>0.3</td>
<td>0.004444</td>
</tr>
<tr>
<td>0.4</td>
<td>0.00592</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0074</td>
</tr>
<tr>
<td>0.6</td>
<td>0.00888</td>
</tr>
<tr>
<td>0.7</td>
<td>0.01036</td>
</tr>
<tr>
<td>0.8</td>
<td>0.01184</td>
</tr>
<tr>
<td>0.9</td>
<td>0.01332</td>
</tr>
<tr>
<td>1</td>
<td>0.0148</td>
</tr>
</tbody>
</table>

Fig. 3. SNR.

acquisition time (more time means more samples and better uncertainty), we can obtain the plot in Figure 3.

In this plot, the SNR is estimated as a function of dwell time for different values of the air flow. It is immediately intuitive to see that without air flow there is little possibility of detecting low activities reliably. By selecting one liter per second, we can be sure that the target activity can be measured with $\text{SNR} = 10$ within little more than two hours. Clearly, there are limitations: the detectors are hardly 100% efficient in detecting any type of radiation; alpha in air have a $\sim 3$ cm mean free path, therefore only decays within a few cm from the detector surface stand a chance of being detected. For our design, we assumed as a starting point a 1 lt/sec nominal flow. We designed a tubing system capable of moving such a flow (provided by an appropriate fan) to a measuring chamber (110x150x38 mm$^3$) with minimal losses and with the ability to completely eliminate ambient light coming from the outside, as our detectors are light-sensitive. The tubing system with the measurement chamber and the electronic platform are shown in Figure 4.

D. Hardware and Firmware

Figure 5 shows the block diagram of the development platform designed to test the system. Additionally to the electronic read-out components, previously described, the device includes an ultra-low-power 32 bit microcontroller (STMicroelectronics) that directs the operations of all the sensors present on-board. The microcontroller has been programmed in order to receive the comparator signal from the analog front-end circuit and to collect environmental data from temperature, humidity and pressure sensors. Wireless communication is implemented by a Bluetooth module (BT33). This transfers to an external device (PC or mobile device) the acquired sensors data and the Radon concentration value calculated by the system. The wireless transfer can also take place through radio frequency communication (RFID) thanks to a dual interface EEPROM memory (STMicroelectronics) presents on-board and connected with a planar antenna. RFID communication, ISO-15693 compliant, offers the possibility of reading the processed data (Radon concentration) via an external RFID...
reader, without additional power consumption in the system. The platform is powered by a Li-ion battery with 300 mAh capacity and has small dimensions (33x28x3.5 mm$^3$). The system can also be powered and recharged by USB connection to a PC or tablet.

The board is assembled on a two layers 80x34 mm$^2$ standard FR4 PCB with commercial components (Figure 6). The firmware controls SiPM bias, timers and interrupts and monitors the comparator output voltage for signals. The detection threshold is set via an internal DAC. When the system is enabled, the microcontroller receives pulses coming from the output comparator, corresponding to the number of detected alpha particles and it increments a variable for each impulse. In order to calculate the mean value of the counted particles and then the number of Radon decays per second (in Becquerel), we configured an internal Real Time Clock (RTC), that enables an interrupt for reading the incremented variable every 60 seconds. The calculated value is transmitted by Bluetooth to an external device, previously paired with the platform. In addition to Radon concentration, the Bluetooth module transmits each minute humidity and temperature values given by the humidity sensor (HIH6130, Honeywell) and of the absolute pressure by the pressure sensor (NPA-700, General Electric).

E. Preliminary Results

Preliminary tests were carried out in a laboratory setting, in order to validate the readout electronics connected to the Silicon Photomultiplier. The experiments have been performed placing an alpha source (1nCi Am-241) on the active area of the ZnS scintillator coupled with the SiPM. Initially the system and the radioactive source have been placed in a dark enclosed box without system ventilation. Figures 7 and 8 show the alpha response of the third analog stage voltage output with one pixel and 16 pixels of the SiPM connected at the input. It is worth mentioning that the peak duration of one alpha signal is less then 1 ms. RMS values of the baseline were calculated when 1 pixel is connected (2 mV) and with the whole SiPM-array connected (63.5 mV). High SNR allows easy discrimination between alpha pulses and noise.

The peaks count was performed varying the distance between the alpha source and the detector. Data acquisition are reported in Table II. The plot in Figure 9 shows the cumulative histogram of the peak counts obtained during a 1 hour long acquisition where the source was placed on the detector. The mean count value is 1048 counts per second.

The 10% difference between the 1-hour acquisition and the 8-hours acquisition demonstrates that the system gives
a sufficiently reliable value of alpha decay rate within one hour. Further measurements were performed in order to validate the whole system with tube ventilation, fan and the electronic platform. We analysed the correlation between the Radon fluctuations and humidity, temperature and atmospheric pressure variations in the laboratory environment. Access to the laboratory was controlled by a normally closed door. The system was programmed to record Radon activity, temperature, relative humidity and absolute atmospheric pressure each minute for about 85 hours. The stored results of Radon concentration was averaged hourly. The data obtained in the hourly record of humidity, temperature, pressure and Radon concentration are shown in Figure 10.

The averaged value of Radon concentration calculated during the acquisition is about 5 Bq/m$^3$. The acquisition was done with a discriminator threshold (500 mV) higher then 5-sigma value of the baseline noise. As expected, the trends observed in Radon concentration were similar to those observed for humidity. The correlation with temperature, however, did not seem strong. Correlation coefficients were calculated for Radon concentrations and environmental data. The highest correlation coefficient value ($R = 0.4553$) was obtained for atmospheric Radon concentration and humidity. Lower correlation coefficient values were obtained for temperature ($R = -0.2392$) or atmospheric pressure ($R = -0.3259$). In the two last cases, the correlation may be considered as not relevant. Moreover, the acquisition shows that the maximum Radon level in the laboratory was observed during the night, when the laboratory is closed and there is no exchange between indoor and outdoor air. Another test was carried out lowering the comparator threshold to 400 mV. With similar atmospheric laboratory conditions, the developed platform has measured a value of Radon concentration of about 55 Bq/m$^3$. The averaged Radon activity values obtained from the two previous acquisitions resulted to be much lower than the mean value (190 Bq/m$^3$) measured by a commercial device (Corentium Canary). The reasons for this discrepancy could be attributed to various factors, such as detection algorithms, calibration and offset consideration, not only for the presented device but also for the commercial system. In fact, Corentium device is able to give reliable values of Radon concentration only after several weeks. Moreover, the developed platform, currently, doesn’t detect the amplitude of the alpha peaks, so it is unable to discriminate the overlapping alpha particles that simultaneously hit the sensitive area of the scintillator. Further studies and long term acquisitions and calibrations will focus on finding the optimal threshold, due to the available margin around the 5-RMS noise value.

III. CONCLUSION

A wireless, battery-powered portable prototype of Radon sensor has been built featuring a SiPM as the alpha particle detector and a simple readout electronics. The developed system composed by fan, ventilation tube and electronic components, has been designed in order to measure continuous Radon indoor concentrations and to provide reliable values in a few hours (about three). The platform is able to record environmental data (relative humidity, temperature, absolute pressure) each minute and to communicate them via Bluetooth to a smart device (PC or mobile device), in order to give a correlation between environmetal parameter fluctuations and Radon concentration. Preliminary measurements have demonstrated a positive correlation between relative humidity and alpha concentration and negative correlation with temperature. Further acquisitions are in progress in different conditions with the aim of finding the optimal system settings and fully validate the device.

REFERENCES