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Sub-milliwatt spectroscopic personal radiation device based on a silicon photomultiplier

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ABSTRACT

A novel spectroscopic personal radiation device (SPRD) with sub-milliwatt power consumption is proposed. The SPRD is based on a compact, low-power, high-gain silicon photomultiplier (SiPM) coupled to a high-light-yield CsI(Tl) scintillator. The SiPM is operated in a special mode, in which its output is voltage rather than charge. In this mode, the SiPM output becomes higher and rises more slowly than in the charge amplification mode. Such a mode allows us to use a lower-frequency front-end amplifier with a lower gain and lower power consumption. Moreover, the very beginning of the slower, large-amplitude pulses is easier to detect with a comparator. At each detection event, the rest of the SPRD circuitry is activated only for the time needed for the pulse-processing. Because at background the radiation count rate is very low, some tens per second, and the duration of the signal-processing is very short, about 10 μ s, the power-demanding SPRD circuitry is not activated most of the time, and its average power consumption is very low. Proper matching of the scintillator and the SiPM helps us to achieve the required gain from the radiation sensor with a relatively low-power, low-gain front-end amplifier. Optimizing the input impedance of the front-end amplifier helps us to obtain the required SiPM output amplitude and shape. Because it takes some time for the signal processing circuit to be activated, an additional passive delay and shaping circuit is used. An experimental model of this device is built, and tested. It is superior to other devices due to its very low power consumption, its portability, and its non-sensitivity to microphonics. The power consumption of the SPRD is about 0.3 mW by the radiation sensor and about 0.3 mW by the electronics (for a total of 0.6 mW as compared to above 20 mW consumed by conventional spectroscopic radiation devices). The power consumption has been measured at count rates up to a few hundreds per second, which are much higher than expected in practice.

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1. Introduction

The homeland security market requires advanced spectroscopic personal radiation devices (SPRDs) for both radioactivity detection and radionuclide identification to target malicious activities. The requirements for SPRDs are given in the latest ANSI 42.48 [1].

Conventional radiation identification devices (RIDs), [2] being traditionally based on photomultiplier tubes (PMTs), are cumbersome, need a high bias voltage, and consume high power [3]. Alternative light detectors, such as PIN diodes and avalanche photo diodes, also require high-power, low-noise amplifiers (LNAs) [3].

To render conventional RIDs portable, their power consumption should be substantially decreased. In conventional RIDs, the power consumption is about 10 mW for the radiation sensor and about 10 mW for the electronics. To substantially decrease the total power consumption, both these components should be minimized.

In this work, we minimize the first component (to 0.3 mW) by employing a new type of radiation sensor based on a low-power light-sensing device: a silicon photomultiplier (SiPM).

To minimize the power consumption of the electronics, we operate the pulse-processing part of it in a power-gating mode (see Fig. 1): The power is enabled only when gamma-photon interactions with the radiation sensor occur. These events are detected by the comparator, and the logic block synchronizes the power gating and the integrator operation. The power gating of the pulse-processing electronics allows us to make its power consumption negligible compared to that of the rest of the electronics.

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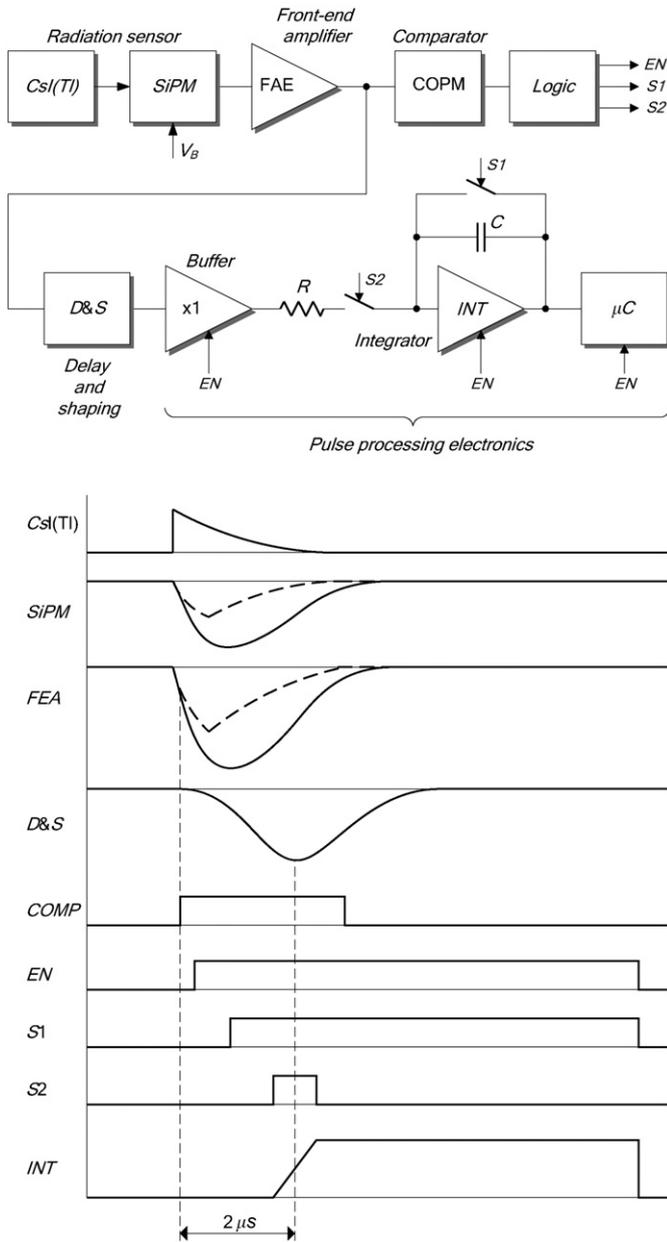


Fig. 1. Spectroscopic portable radiation device based on a SiPM. Schematic and time diagrams (the outputs of the device components as a function of time). The dashed lines show the pulse shapes that would be obtained for a charge front-end amplifier.

To reduce (to 0.1 mW) the power consumption of the front-end amplifier, we minimize its speed. We use a voltage rather than a charge front-end amplifier, and this increases both the width and the amplitude of the pulses at its input (see Fig. 1). As a result, it becomes possible to use a front-end amplifier with a lower gain-bandwidth product and, hence, with lower power consumption.

The remaining major power consumer (0.2 mW) is the comparator; thus, the total power consumption of the electronics (0.3 mW) matches that of the radiation sensor (0.3 mW).

The low power consumption of the developed SPRD allows a month-long operation from a single AAA battery compared to a few hours operation of a RID based on a PMT. This is not only because of a greater power consumption of the PMT but also because of the much lower efficiency of the voltage converter that

converts the low batteries voltage into a very high bias voltage of the PMT.

2. Radiation sensor

2.1. Selecting the scintillator and SiPM couple

To integrate an SiPM into the radiation sensor, we have analyzed the matching between commercially available scintillators and SiPMs. Fig. 2 shows the wavelength correspondence between the scintillators and SiPMs, and Table 1 lists the parameters of the scintillators.

The wavelength correspondence and the light yields of the scintillators (see Table 1) give us the signal yields for different types of SiPMs (see Table 2). Table 2 shows that the CsI(Tl)–SensL couple provides the maximum signal yield. Considering the CsI(Tl) scintillator density given in Table 1, a $8 \times 8 \times 30 \text{ mm}^3$ crystal has been selected to meet the sensitivity requirements of the ANSI 42.48 standard.

The three commercially available SensL’s SiPMs have sizes of 1×1 , 3×3 , and $6 \times 6 \text{ mm}^2$. Their power consumption increases with size. To minimize the power consumed by the radiation sensor, we have chosen an SiPM of the SPM3035 [7] type with a size of $3 \times 3 \text{ mm}^2$. These are the minimal dimensions that provide low enough noise (see Fig. 3). The selected SiPM consumes about 0.3 mW.

2.2. Temperature stability

As seen from the above, we have modified the radiation sensor and the electronics to reduce the SPRD’s total power consumption. In the radiation sensor, the conventional PMT has been replaced with an SiPM. The SiPM noise and gain are high enough to neglect the contribution of the subsequent electronic stages to

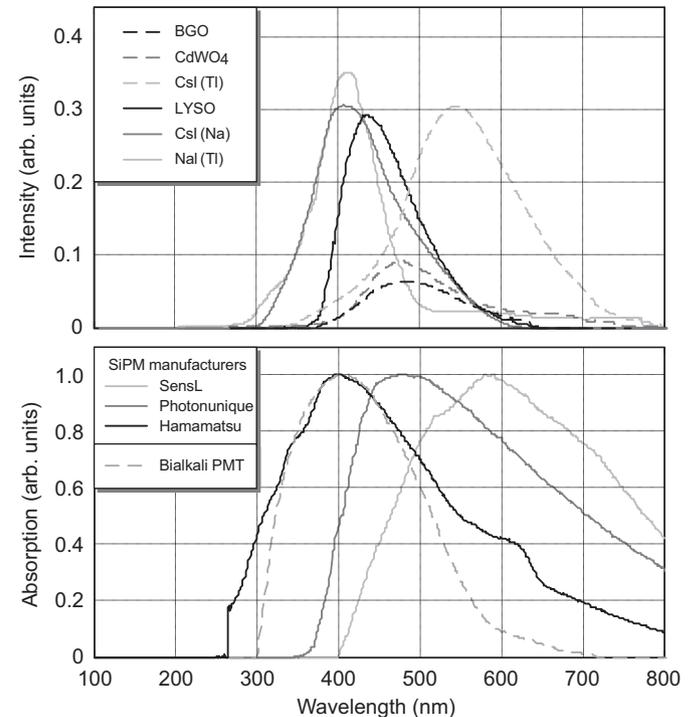


Fig. 2. Wavelength matching between the scintillators and SiPMs. Emission spectrums of scintillators (top). Absorption spectrums of SiPMs (bottom). For comparison, the absorption spectrum of a Bialkali PMT is shown as the dashed line.

Table 1
Properties of scintillators.

Scintillation crystal	Density (g/cm ³)	Light yield (ph/MeV)	Decay time, τ (μ s)	Hygroscopicity	Intrinsic radioactivity
BGO	7.13	9000	0.3	None	None
CdWO ₄	7.90	13,500	14.0	None	None
CsI(Tl)	4.51	54,000	1.0	Low	None
LYSO	7.10	32,000	0.041	None	Present
NaI(Tl)	3.67	38,000	0.25	High	None
CsI(Na)	4.51	41,000	0.63	High	None

The hygroscopicity of the CsI(Tl) scintillator is considered to be low enough for practical purposes.

Table 2
Relative signal yields of different types of radiation sensors compared to an NaI(Tl) scintillator coupled to a Bialkali PMT.

Scintillation crystal	Signal yield of different types of light detectors			
	Bialkali PMT	SiPMs		
		Hamamatsu MPPC	SensL SPM	Photonique SSPM
BGO	0.17	0.21	0.27	0.19
CdWO ₄	0.23	0.29	0.38	0.29
CsI(Tl)	0.60	0.94	1.44	1.41
LYSO	0.81	0.87	0.89	0.48
NaI(Tl)	1.00	1.04	0.69	0.30
CsI(Na)	1.10	1.14	0.85	0.40

The relative signal yields include only the wavelength correspondence and the number of initially produced photons.

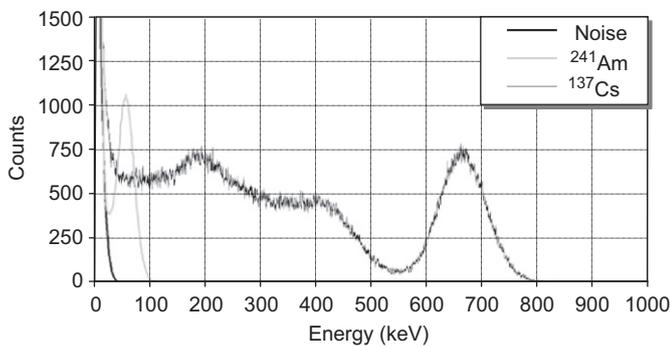


Fig. 3. Energy spectra of the selected scintillator and the light sensor: CsI(Tl) and SPM3035.

the device total noise. Moreover, the SiPM is more temperature sensitive than the electronics. For these reasons, we have addressed only the effect of the radiation sensor modification on the device's precision, neglecting the effect of the electronics modification.

Temperature affects the gain [4], the avalanche initiation probability (AIP) [5], and the SiPM noise. Both the gain and the AIP are functions of the over-voltage V_{OV} that equals the difference between the bias voltage V_B and the SiPM breakdown voltage V_{BR} :

$$V_{OV} = V_B - V_{BR} \quad (1)$$

$$V_{BR} = V_0 + \alpha \Delta T \quad (2)$$

where V_0 is the breakdown voltage at a given temperature T , α is the temperature coefficient, and ΔT is the temperature change.

As seen from Eqs. (1) and (2), for $V_B = \alpha \Delta T + V_B$ where V_B is the bias voltage at T , $V_{OV} = V_B - V_0$. Thus, both the SiPM gain and the AIP become temperature insensitive. For the SPM3035, α has been measured to be 21 mV/°C, and V_{OV} was set at 1.5 V.

To be sure that the identification functionality is not disrupted by the SiPM noise, we have measured the ¹³⁷Cs resolution

(see Fig. 3) at the highest temperature (50 °C), required by standards. The full width at half maximum (FWHM) resolution at 50 °C is 15%, which is only by 2% worse than at room temperature.

3. Electronics

3.1. Power gating of the signal-processing electronics

Direct application of power gating to the pulse-processing electronics of conventional RIDs is not effective due to the short duration of the radiation pulses at the front-end amplifier output (see Fig. 1); the processing electronics does not activate quickly enough to catch the radiation pulse.

To make the radiation pulses longer, we use a voltage rather than a charge front-end amplifier and optimize its input impedance to increase the radiation pulse duration without significantly increasing the noise (see Section 3.2). We also use a delay and shaping circuit to further increase the radiation pulse width (see Fig. 1). These increases provide enough time (about 2 μ s) for the integrator to wake up. Due to the long memory of the integrator, its output can be read by the microcontroller μ C, which activates in about 5 μ s.

Employing the integrator helps us to avoid decreasing the signal-to-noise ratio (SNR), because, delaying the radiation pulse with the analog shaper by 5 μ s instead of 2 μ s would collect more noise.

Selecting a scintillator with a decay constant shorter than 1 μ s would shorten the radiation pulse. A front-end amplifier with a higher gain and higher power consumption should be used in that case to compensate for the higher reduction of shorter pulses by the delay and shaping circuit.

A CdWO₄ scintillator, with a very long decay constant, would allow us to simplify the electronics by omitting the delay and shaping circuit. We have not selected, this type of scintillator, however, because radiation sensor pulses that too long would gather too much SiPM noise.

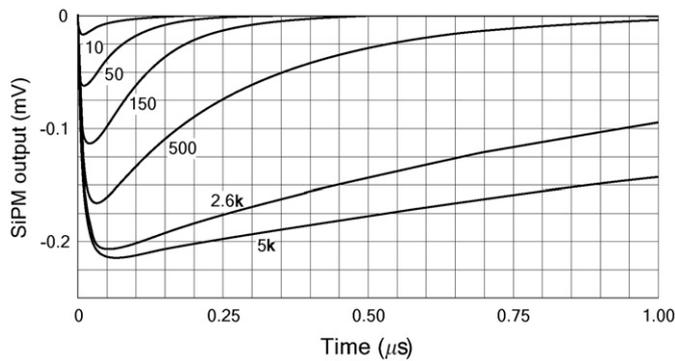


Fig. 4. SiPM time response to a single microcell activation. The input impedance of the front-end amplifier is shown as a parameter.

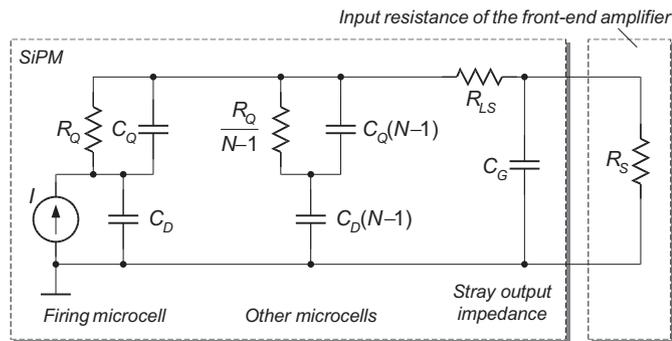


Fig. 5. Equivalent electrical circuit of the SiPM.

3.2. Front-end amplifier

As mentioned above, employing a voltage rather than a current front-end amplifier increases the radiation pulse duration. Moreover, this also increases the magnitudes of the radiation pulses. As a result, it is possible to use a front-end amplifier with a lower speed and, hence, lower power consumption.

To optimize the input resistance of the front-end amplifier, we have analyzed its effect on the shape of the radiation sensor's output. This output is a superposition of the SiPM's microcell activations. Fig. 4 shows the SiPM time response to a single microcell activation in accordance with the SiPM's characteristics [6] and its equivalent electrical circuit [7] (see Fig. 5).

I in Fig. 5 is the equivalent current source that injects an electrical charge generated by a microcell discharge. C_D is the parasitic capacitance of the microcell, R_Q is the quenching resistor, C_Q is the parasitic capacitance of the quenching resistor, C_G is the parasitic capacitance between the SiPM output terminal and the SiPM gage, R_{LS} is the series parasitic resistance of the SiPM, and R_S is the input resistance of the front-end amplifier. We neglect the input capacitance (about 10 pF) of the front-end amplifier compared to C_G (about 100 pF).

One can see from Fig. 4, that increasing the input resistance of the front-end amplifier increases both the amplitude of the SiPM time response and its duration. One can also see that for relatively high values of R_S , the time-response amplitude grows insignificantly, whereas its decay time continues to increase. As a result,

more noise is integrated at the moment when the pulses reach their maxima, and the SPRD's SNR decreases. Hence, a tradeoff is necessary between increasing the SiPM's output pulse amplitude and decreasing the SNR. Our simulations and experiments have shown that the optimum value of the input resistance is 2.6 k Ω .

4. Summary and conclusion

A new low-power SPRD has been developed, built, and tested. The power consumption has been reduced by more than an order of magnitude (to 0.6 mW) compared with that of conventional devices (above 20 mW). Such a significant power reduction has been obtained by replacing the PMT in the radiation sensor with a new, and much more power-efficient type of light sensor: the SiPM. In addition, the power consumption of the electronics has been reduced to match the power consumption of the SiPM.

The SiPM is operated in a special mode, where its output is voltage rather than charge. In this mode, the SiPM output becomes higher and rises more slowly. This has allowed us to use a lower-frequency front-end amplifier with a lower gain and lower power consumption.

To maximize the radiation sensor efficiency, we have selected the CsI(Tl)–SPM3035 couple, after considering the wavelength correspondence, light yield, the scintillator density, and SiPM size.

We have selected the CsI(Tl) scintillator with a 1- μ s decay constant, because longer radiation pulses would collect more SiPM noise. For shorter radiation pulses, a front-end amplifier with a higher gain and higher power consumption should be used to compensate for more significant reduction of shorter pulses by the delay and shaping circuit.

A temperature-dependent bias voltage has been used to reduce the temperature sensitivity of the SiPM.

An experimental prototype has been built and tested. Due to the integration of the SiPM into the radiation sensor and also due to the modification of the electronics, the prototype has become low-power and compact enough to meet the standards for SPRD.

Integrating the SiPM into the radiation sensor also provides additional advantages such as low bias voltage, robustness, and insensitivity to microphonics and ambient magnetic fields [8].

The newly developed device provides a 40 keV noise level and 13% FWHM resolution for the ^{137}Cs . It could be used in homeland security applications to target malicious activities by detecting radioactivity and identifying radionuclides.

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