Signal Detection System Based on Charge Integration for Flexible Perovskite x/γ Detectors

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Abstract

This study designs a flexible x/γ perovskite detector signal monitoring system based on charge integration, consisting of three components: a flexible acquisition circuit, a signal processing unit, and a human-computer interaction system. The flexible acquisition circuit constructs a flexible Faraday cage using a circuit board and double-layer electromagnetic shielding film, effectively suppressing environmental noise. The signal processing circuit implements continuous acquisition of picoampere-level current signals (accuracy 0.3 pA) through a two-channel time-division serial charge integration circuit. The human-computer interaction system, developed based on C#, supports real-time processing and storage of 64-channel data. Experimental verification demonstrates that the self-developed system achieves a current measurement error of less than 1% within the 10 nA to 10 pA range, with an average signal-to-noise ratio of 49.98 dB, significantly outperforming commercial equipment (41.45 dB). In energy response experiments, the linear fitting goodness-of-fit between dose and charge quantity (R^2=0.997) shows good consistency with commercial devices. Designed for flexible perovskite x/γ detectors, this system combines high precision, lightweight characteristics, and anti-interference properties, establishing a solid foundation for dose applications of flexible perovskites in radiation protection, medical monitoring, and other fields.

Full Text

Preamble

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A Flexible Perovskite X/γ Detector Signal Detection System Based on Charge Integration

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Abstract

This study designed a flexible X/γ perovskite detector signal monitoring system based on charge integration. The system consists of three components: a flexible acquisition circuit, a signal processing unit, and a human-machine interaction system. The flexible acquisition circuit constructs a flexible Faraday cage through a circuit board and double-layer electromagnetic shielding film, effectively suppressing environmental noise. The signal processing circuit employs two time-sharing serial charge integration circuits to continuously collect picoampere-level current signals (with an accuracy of 0.3 pA). The human-machine interaction system, developed using C#, supports real-time processing and storage of 64-channel data. Experimental verification demonstrates that the self-developed system achieves a current measurement error of less than 1% within the range of 10 nA to 10 pA, with an average signal-to-noise ratio of 49.98 dB, significantly outperforming commercial equipment (41.45 dB). In energy response experiments, the goodness of fit (R^2 = 0.997) between dose and charge quantity is excellent, showing strong consistency with commercial devices. Designed for flexible perovskite X/γ detectors, this system features high precision, lightweight construction, and anti-interference characteristics, laying a solid foundation for dose applications of flexible perovskite in radiation protection and medical monitoring.

Keywords: Flexible; Charge integrated circuit; Perovskite electrode; Signal-to-noise ratio

Introduction

In radiotherapy and emergency accident scenarios, real-time and accurate measurement of personnel radiation dose is typically difficult to achieve, often requiring dose estimation through Monte Carlo simulation based on spatial relationships between radiation sources and individuals [1, 2]. However, these data represent theoretical calculations rather than actual monitoring values. Currently, widely used practical personal dosimetry devices primarily include thermoluminescent dosimeters (TLD) and Geiger-Müller tube-based electronic personal dosimeters (EPD) [3-5]. Nevertheless, these devices generally suffer from large volume and inconvenience for portable use. Although modern personal dosimetry devices have achieved technical optimization in detection accuracy and portability, numerous limitations persist in practical applications.

Personal dosimetry devices exhibit significant limitations: their single-point measurement characteristic only captures localized dose data at the wearing position, failing to reflect three-dimensional dose distribution across the body surface or within tissues. This measurement constraint means that readings from specific points cannot accurately assess overall exposure dose levels. Current commercial dosimetry devices (both active and passive) generally have large volumes and poor wearing comfort, as explicitly discussed in literature [6].

Breakthroughs in flexible electronics technology provide new directions for dosimetry device innovation. Electronic devices based on flexible substrate materials offer ultra-thin, stretchable, and biocompatible characteristics, significantly improving device conformity and signal acquisition stability. This technology has achieved industrial breakthroughs in medical sensing and wearable devices, with innovative applications of flexible sensors and smart patches in biomedical monitoring [7-9].

The rapid development of flexible substrate electronic devices has created a significant ripple effect for dosimeter flexibility. Radiation protection requirements for flexible materials include both lightweight/foldable characteristics and γ/X-ray response capabilities. Recently developed perovskite materials can satisfy both requirements, though practical applications still face challenges [10]. When excited by γ/X-rays, these materials typically generate current signals limited to the nA to pA range, while environmental noise is generally high. If detectors are placed in ambient environments, they are highly susceptible to interference [11], resulting in perovskite measurements often requiring expensive, high-precision commercial signal acquisition equipment that is generally costly and bulky, severely restricting the development and practical implementation of perovskite detectors. Additionally, most high-performance perovskite materials cannot be fabricated into flexible substrate forms through conventional processes [12, 13].

Therefore, designing a detector circuit suitable for flexible perovskite is extremely important. Accordingly, this study developed a detector circuit and host computer system adapted for flexible γ/X-ray detection. This system features multi-channel acquisition capability, enabling dynamic monitoring of surface dose distribution through flexible detector arrays, and represents pioneering exploration toward miniaturization and further dose applications of flexible perovskite detector systems.

In this study, a perovskite electrode material of $[NH_3(CH_2)_4NH_3]BiI_5$ was selected [14]. Based on the electrical properties of this electrode, the design requirements for the acquisition circuit were thoroughly analyzed. First, due to the inherent characteristics of perovskite materials, the electrode exhibits a dark current of approximately 10 pA in the non-excited state. Under radiation excitation, the difference between excited current and dark current typically remains around 100 pA. Therefore, the acquisition circuit must achieve extremely high current collection precision, at least at the picoampere level or even lower, to ensure accurate capture of these weak current variations. This requirement is highly challenging in natural environments, as ambient noise typically reaches the microvolt level, sufficient to interfere with and mask weak effective signals. Second, as the perovskite electrode is a semiconductor electrode with no dead time and fast response time, higher requirements are imposed on signal sampling rates. Finally, considering the flexible characteristics of the perovskite electrode, special considerations must be made in circuit design and processing technology. In flexible circuits, one of the most common and troublesome issues is noise generated by circuit deformation. Addressing these three special requirements, this study developed a signal acquisition system with 0.2 pA acquisition precision, successfully achieving accurate collection of picoampere-level current signals. The overall system diagram is shown below.

[Figure 1: see original paper] System Diagram

2.1 Flexible Acquisition Circuit Design

This acquisition circuit achieves comprehensive electromagnetic shielding against signal interference, ensuring minimal impact on collected signals during skin-contact wearing and human movement operations. The main structure consists of an FPC circuit and upper/lower electromagnetic shielding films. The two shielding films completely envelop the circuit, forming a flexible Faraday cage that minimizes signal interference. Meanwhile, the bottom two layers serve as reinforcement plates, ensuring the overall circuit possesses strong flexibility and wear resistance to prevent breakage and wear during skin-contact wearing. As shown in Figure 2A, the flexible circuit board contains two signal acquisition circuits: one for the flexible perovskite detector signal and another for reference signal acquisition (reference capacitor). Both acquisition circuits connect to a 10 V bias voltage. To facilitate signal acquisition and industrial processing convenience while improving product yield, the interdigital electrode geometry was specially designed. This design integrates with flexible circuit board packaging by increasing the area of the two tail ends of the interdigital electrode and thickening connection points, enabling better contact performance and durability between the interdigital electrode and flexible circuit board. The electrode channel width is 0.06 mm, finger length is 2.74 mm, pad length is 1 mm, and pad width is 2.02 mm. The electrode has 8 fingers and 7 channels. This design allows the perovskite detector to integrate tightly with the flexible circuit while enabling interference-free transmission of response signals. Figure B illustrates the flexible circuit and detector fabrication process: first, reference capacitors are added to the printed flexible circuit board, then the flexible perovskite electrode is adhered to the flexible circuit. Finally, the entire electrode is covered with a 5 m thick aluminum layer. This aluminum layer serves two purposes: first, it encloses the entire acquisition circuit within a Faraday cage, and second, it can serve as compensation material for Hp(0.07) dosimetry. Figure C shows the perovskite detector worn on a hand, and Figure D displays the overall flexible perovskite detector.

[Figure 2: see original paper] Flexible Circuit Production Process

2.2 Signal Processing Unit

This acquisition circuit employs the principle of charge integration, continuously collecting charge released by the perovskite detector and reference capacitor to statistically determine the current and dark current values of both sensors after excitation. One disadvantage of charge integration circuits is their inability to collect charge during the discharge phase after charging. Therefore, this circuit uses two identical charge integration circuits for real-time current acquisition. The charge integration circuit connects to a 20-bit Σ-Δ ADC at the rear end with a sampling rate of 2500 Hz. The charge integration circuit uses a 33 pF feedback capacitor with a maximum analog voltage of 5 V and reference voltage of 1 V. Through formula calculation, the maximum acquisition current is 330 nA, maximum charge quantity is 132 pC, and current precision is 0.3 pA. The two charge integration circuits operate in time-sharing serial mode, enabling continuous current acquisition.

2.3 Acquisition Software Design

The data acquisition software used in this study was developed using the C# programming language and built on the .NET 8.0 framework, providing users with a stable, efficient, and user-friendly data processing platform. The software can simultaneously display information for up to 64 channels. Through USB interface connection with hardware devices, the software achieves real-time acquisition and display of uploaded data, and supports saving parsed data in Excel format for further user analysis and processing. The software interface includes a real-time data display area that dynamically shows data received from hardware devices. The electrometer sends data at 250 packets per second (2500 frames) through USB, with each packet containing 10 frames and each frame being 166 bytes long. The data processing software receives data in real-time through USB and employs multi-threading technology for processing. Additionally, the software supports multi-channel data display for convenient user comparison and analysis. The software also features the ability to save parsed data as Excel files for data organization, analysis, and report generation. Users can configure baselines, sampling rates, ranges, and X/Y axis display ranges according to actual needs, facilitating accurate data judgment. The overall software framework is shown in Figure 3A, and the interface is shown in Figure 3B.

[Figure 3: see original paper] Software Frame and Software Screenshot

3.1 Circuit Verification

To verify the correctness of current values collected by the circuit, this study used a Tektronix AFG31000 waveform generator [15] to continuously emit square waves of specific amplitudes: 2 mV, 4 mV, 6 mV, 8 mV, and 10 mV. Precision resistors with 0.1% tolerance were then added to the stimulus circuit with values of 100 kΩ, 1 MΩ, 10 MΩ, 100 MΩ, 1 GΩ, and 10 GΩ. According to Formula 1, the calculated current range was between 100 nA and 0.2 pA. This study simultaneously used a commercial Keysight B2901 source meter [16] and the self-developed circuit to collect the aforementioned currents. The connection circuit for acquisition is shown in the figure. By analyzing both sets of data against the standard source, current acquisition accuracy was verified.

[Figure 4: see original paper] Experimental Circuit

3.2 Circuit Signal-to-Noise Ratio Verification

Since all collected currents are below the µA level, environmental noise easily mixes into the acquisition circuit. This study evaluated signal purity using Signal-to-Noise Ratio (SNR) [17]. The effective signal power is represented by a straight line (Ps) drawn through the average values of measurement signals at the same level position. Pn is the noise signal power, obtained by subtracting the effective signal from the original signal. The signal power calculation method is shown in Formula 2, and the SNR calculation method is shown in Formula 3 [18]. The SNR for each level data was analyzed, and all SNR results were averaged to obtain the final SNR parameter for the device.

3.3 Linear Response Experimental Verification

This study conducted an on-site experiment to verify the detector' s linear response. A Co-60 source was used to test the perovskite detector at dose rates of 5.579 Gy/h, 1.387 Gy/h, 0.884 Gy/h, 111.1 mGy/h, 26.76 mGy/h, and 16.87 mGy/h. After connecting the commercial source meter and setting each dose rate, the background current was first recorded, the Co-60 radiation device was activated to record the excited current, the device was turned off, and the test was repeated three times before proceeding to the next dose rate. The same procedure was then repeated using the self-developed module.

3.4 Energy Response Experimental Verification

This study experimentally tested the detector's energy response. The perovskite detector was evaluated using X-rays at a dose rate of 430 µGy/h. X-ray energy levels were set at: 208 keV, 164 keV, 118 keV, 83 keV, 48 keV, and 33 keV. A commercial source meter was used in the experiment. After each energy adjustment, the background current was first recorded, the X-ray radiation equipment was activated to record the excited current, the equipment was turned off, and this process was repeated three times. The same test procedure was then performed using the self-developed module.

3.5 Angle Response Experimental Verification

This study experimentally tested the detector' s angle response. The perovskite detector was evaluated using X-rays at a dose rate of 29.8 mGy/h and 48 keV energy. X-ray irradiation angles were set at: -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, and 60°. The self-developed module was used in the experiment. After each angle adjustment, the background current was first recorded, the X-ray radiation equipment was activated to record the excited current, the equipment was turned off, and this process was repeated three times. Figure 5 shows the actual measurement scenario.

[Figure 5: see original paper] Experiment

4.1 Circuit Verification Results

Table 1 presents detailed circuit verification results. Analysis of these data reveals that current measurement errors remain at extremely low levels, specifically below 5%. Further observation shows an average error value of 1.90%, indicating very high overall measurement accuracy. Most notably, within the current measurement range of 10 nA to 10 pA, measurement errors are constrained within 1%, highlighting exceptional precision and reliability in ultra-low current measurement.

Current Error Between Self-developed Equipment and Commercial Equipment

4.2 Signal-to-Noise Ratio Experimental Results

This study conducted comparative analysis of signal-to-noise ratio performance between the Keysight B2901 commercial device and the self-developed circuit at different current levels. Detailed data are recorded in Table 2, which comprehensively shows SNR data for the Keysight B2901 at various current levels. Table 3 presents SNR data for the self-developed circuit at the same current levels. Through comparative analysis of data from both tables, a clear conclusion emerges: the commercial device achieves an average SNR of 41.45 dB, while the self-developed circuit reaches an average SNR of 49.98 dB. This result clearly demonstrates that the self-developed circuit consistently achieves higher SNR across different current levels, confirming its advantages in signal processing and suggesting potentially higher accuracy and reliability in practical applications.

SNR of Commercial Equipment

SNR of Self-developed Equipment

4.3 Linear Response Experimental Results

Figure 6 demonstrates the system' s signal detection capability during dose measurement and verifies the relationship between different dose rates and response current for the perovskite detector. The graph clearly shows the meaning of different data point shapes: circular data points represent experimental data collected using commercial equipment, while triangular data points represent data from the self-developed device. To ensure data accuracy and reliability, each device' s data were obtained by averaging three independent measurements. Data point distribution reveals a linear relationship between dose and charge. Linear fitting yielded a slope of 766.08 and intercept of 80.64, with goodness-of-fit R^2 = 0.994, indicating excellent fitting and high consistency between data points and the fitted line. This validates the linear characteristic of the relationship between detector dose rate and current, and further confirms the performance of the signal acquisition system and its compatibility with the perovskite detector.

[Figure 6: see original paper] Relationship Between Dose Rate and Current

4.4 Energy Response Experimental Results

Figure 7 reveals the relationship between radiation energy and response current. The figure clearly shows a significant peak at 48 keV, with responses gradually decreasing at other radiation energies. Both commercial and self-developed devices maintain consistent trends and similar values. The self-developed device demonstrates capability for accurate measurement of perovskite detectors.

[Figure 7: see original paper] Relationship Between Dose Rate and Current

4.5 Angle Response Experimental Results

Figure 8 shows the angle response characteristics measured by the self-developed device. The response exhibits symmetrical patterns because the detector used is a planar type, where X-ray propagation paths change correspondingly with incident angle variations. Experimental results validate the device's effectiveness in detector-related experimental operations. Additionally, the device can be applied for performance testing of perovskite detectors in specific scenarios.

[Figure 8: see original paper] Relationship Between Dose Rate and Current

Discussion

In radiation detection, stable dose response of detectors and precise measurement of signal detection systems are crucial. Based on hotspot perovskite materials and the trend toward flexible dosimetry, this paper discusses a flexible perovskite detector signal detection system based on charge integration circuits. Through specific circuit parameters and materials, this design achieves accurate acquisition and processing of weak current signals. The discussion focuses on analyzing the design principles, circuit verification, SNR evaluation, and energy response experimental results of this signal acquisition system.

First, the charge integration circuit design is based on specific parameters such as a 33 pF feedback capacitor and 5 V maximum analog voltage, enabling the circuit to handle maximum currents of 330 nA and charge quantities of 132 pC, with current precision reaching 0.3 pA—fully meeting the response current range and detection precision requirements of perovskite detectors. Furthermore, through time-sharing serial operation, two charge integration circuits achieve continuous current acquisition, which is highly useful for real-time monitoring of current changes. The flexible circuit design employs FPC circuits and electromagnetic shielding films to form a flexible Faraday cage, effectively reducing signal interference. Meanwhile, reinforcement plates ensure circuit flexibility and wear resistance, which are essential for wearable devices. The signal acquisition circuit design, including both flexible perovskite detector and reference signal acquisition circuits, connects to a 10 V bias voltage, which helps improve signal acquisition stability and accuracy. The acquisition software, developed using C# and the .NET framework, provides a stable, efficient, and user-friendly data processing platform. The software can display multi-channel data in real-time and supports data saving and further analysis. Multi-threading technology ensures real-time and accurate data processing. Circuit verification used waveform generators and precision resistors to simulate current signals, verifying acquisition accuracy through comparison with commercial equipment. SNR experimental results show that the self-developed circuit achieves higher SNR than commercial equipment at different current levels, demonstrating advantages in signal purity. Finally, energy response experimental results indicate good consistency between self-developed and commercial devices in the dose-charge relationship, with fitted linear slopes and intercepts demonstrating that this system achieves commercial-grade accuracy and reliability.

In summary, the signal detection system design presented in this paper demonstrates excellent performance in precise measurement of current and charge quantities. Through optimized circuit design, high-quality materials, and advanced software support, the system can not only accurately measure weak current signals but also provide stable and reliable data in practical applications. This can accelerate portable measurement and application promotion of perovskite materials while holding significant importance for current and charge quantity monitoring in industrial, medical, and scientific research fields.

Conclusion

This paper presents a flexible perovskite X/γ detector signal detection system based on charge integration circuits. Through specific circuit parameters and materials, this design achieves accurate acquisition and processing of weak current signals. The design includes charge integration circuits, signal acquisition circuits, and data processing software. The charge integration circuit can handle maximum currents of 330 nA and charge quantities of 132 pC, with current precision reaching 0.3 pA. The flexible circuit design uses FPC circuits and electromagnetic shielding films to form a flexible Faraday cage [19], effectively reducing signal interference. The data processing software, based on C# and the .NET framework, supports real-time display, saving, and analysis of multi-channel data. Circuit verification using waveform generators and precision resistors simulated current signals and verified acquisition accuracy through comparison with commercial equipment. SNR experimental results show that the self-developed circuit achieves higher SNR than commercial equipment at different current levels. Energy response experimental results also demonstrate good consistency between self-developed and commercial devices in the dose-charge relationship. In summary, this signal detection system demonstrates excellent performance in precise measurement of current and charge quantities, meeting radiation signal detection requirements for perovskite detectors while achieving measurement performance comparable to commercial equipment. This holds significant importance for promoting and applying perovskite materials in radiation detection and lays the foundation for miniaturization and flexibility of dose measurement systems.

Author Contributions

This paper was written by Zhongyan Shi. Research design was completed by Zhongyan Shi, Jing Zhang, and Ri Zhao. Data analysis was performed by Zhongyan Shi and Maolin Wang. Data acquisition was completed by Renjing Linghu and Maolin Wang. Data calibration was performed by Xin Liu. Hardware development was completed by Zhongyan Shi, Renjing Linghu, and Runcheng Liang. Article revision and data verification were completed by Haijing Jin and Zhaoxing Liu.

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Note: Figure translations are in progress. See original paper for figures.