Design and Simulation of Processing Circuit for Step-type Signals in Soft X-ray Detection

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Date: 2024-03-15T00:00:00+00:00

Abstract

In soft X-ray spectroscopy detection, integrated detection devices employing a Silicon Drift Detector (SDD) combined with a reset-type charge-sensitive preamplifier produce staircase sawtooth wave output signals containing spectral information. This paper addresses the problem that the staircase sawtooth signals generated by such devices cannot be directly used to accurately extract amplitude information, proposes a scheme for shaping and amplifying these signals using analog circuits, and investigates the feasibility of this scheme as well as the factors affecting spectral energy resolution through Cadence software simulations. Furthermore, by comparing circuit output signals under different input noise amplitudes, the paper determines the minimum noise specification requirements for the preamplifier output signal to meet the corresponding energy resolution specifications.

Full Text

Design and Simulation of Shaping Circuit for Stepped Signals in Soft X-ray Detection

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Abstract

In soft X-ray energy spectrum detection, integrated detection devices that combine a Silicon Drift Detector (SDD) with a reset-type charge-sensitive preamplifier output a stepped sawtooth wave containing spectral information. This paper addresses the challenge that amplitude information cannot be directly extracted from such stepped sawtooth signals, proposing an analog circuit scheme for signal shaping and amplification. Through Cadence software simulation, we investigate the feasibility of this approach and identify factors affecting the energy resolution of the resulting spectra. By comparing circuit outputs under different input noise amplitudes, we determine the minimum noise specifications required for the preamplifier output signal to meet the specified energy resolution requirements.

Keywords: Silicon Drift Detector; stepped voltage signal; soft X-ray energy spectrum; signal shaping
CLC: TL814; TN710; TP391.9

Soft X-ray (energy range 1-20 keV) spectroscopy is a routine diagnostic for electron temperature measurement on the Experimental Advanced Superconducting Tokamak (EAST). The recently developed SDD offers advantages over traditional Si(Li) detectors, including smaller size, higher detection efficiency, and better energy resolution, making it well-suited for electron temperature diagnostics in tokamak devices [1]. During operation, SDDs in the detector array detect characteristic X-rays radiated from the tokamak port. After internal integration with a reset-type charge-sensitive preamplifier, the system outputs a sawtooth wave containing X-ray spectral information. The observed output waveform is shown in [Figure 1: see original paper].

[Figure 1: see original paper] illustrates the detailed view within the circled region, showing outputs for two different energies: 5.9 keV and 22.1 keV. Each soft X-ray photon produces a positive amplitude of 3.7 mV/keV. Since this signal is a stepped sawtooth wave with approximately 2 V amplitude, the energy spectrum cannot be directly obtained. Therefore, the signal must first undergo preliminary shaping and amplification through a front-end signal conditioning unit to produce nuclear pulse signals of appropriate amplitude. These pulses are then sampled by a high-speed ADC and processed by an FPGA for digital filtering, baseline restoration, pile-up rejection, and amplitude extraction, ultimately yielding the soft X-ray spectral information [2]. The system design requirements are specified in .

A critical challenge in this system is how to shape the stepped sawtooth signal shown in [Figure 1: see original paper] into unidirectional nuclear pulses while minimizing noise impact to ensure the measured spectrum meets the energy resolution requirements.

1 Reset-Type Charge-Sensitive Preamplifier

The reset-type charge-sensitive preamplifier circuit used in the system is schematically shown in [Figure 2: see original paper]. During normal operation, current pulses from the detector accumulate charge on feedback capacitor Cf, with each pulse raising the output level by a corresponding amount to produce a stepped voltage signal. When the level reaches a certain threshold, it triggers the reset pulse and pulse suppression circuit, generating a positive pulse signal that increases the gate current Ig of field-effect transistor Q, thereby discharging the accumulated charge on Cf. Consequently, the preamplifier output exhibits a sawtooth waveform. The reset-type charge-sensitive preamplifier employed in this system has an output dynamic range of 2 V, converting each 1 keV of radiation energy into a 3.7 mV voltage step.

2.1.1 Differential Circuit Fundamentals

Differentiation is commonly used to convert stepped signals into pulse signals. The schematic of an improved differential circuit is shown in Figure 5: see original paper [3]. The output of this differential circuit is V2 = -R1C4 • dV1/dt, producing a signal that is the derivative of the input level. The output waveform only reflects abrupt changes in the input, generating output only during transitions while producing no output for constant portions. Resistor R3 is added in series with the input loop, and a small capacitor C1 is paralleled in the feedback loop, with R3C4   R1C1 preferred. At normal operating frequencies, the effects of R3 and C1 are negligible, but at high frequencies they reduce the closed-loop gain, thereby suppressing high-frequency noise. Additionally, R1C1 forms a lead compensation stage that improves circuit stability.

2.1.2 Differential Circuit Simulation

Using the Stimulus Editor function in Cadence, custom excitation sources can be created. For example, a stepped voltage signal superimposed with Vpp = 5 mV Gaussian white noise is shown as V1 in [Figure 3: see original paper]. This waveform contains four steps of different amplitudes, where the smallest step represents 1 keV radiation output (3.7 mV) and the largest represents 20 keV output (74 mV). When this signal is input to the circuit in Figure 5: see original paper, the simulated output V2 is obtained as shown in [Figure 3: see original paper]. The differential circuit successfully converts the stepped signal into negative pulses, but V2 exhibits noise with Vpp   300 mV. Given that noise is inevitable in practical systems, further processing of V2 is necessary to achieve higher energy resolution by reducing noise impact.

2.2.1 Integral Circuit Fundamentals

For unidirectional pulse signals, integration can optimize the signal-to-noise ratio since noise amplitudes are typically bidirectional. The integral circuit schematic is shown in Figure 5: see original paper, with output signal V3 = -(1/R2C2) V2 dt. To prevent saturation of the integrating capacitor C2, a discharge resistor R2 is paralleled in the feedback loop. Since R2 is connected across the capacitor, it drives the capacitor voltage toward zero regardless of polarity, preventing unbounded growth or decay. However, R2 cannot be too small, as this would transform the integrator into a low-pass filter [4].

2.2.2 Integral Circuit Simulation

Maintaining the same excitation signal at the differential circuit input (the stepped voltage V1 from [Figure 3: see original paper]), the output V2 from the differential circuit is used as the input to the integral circuit. Cadence simulation yields the output voltage waveform V3 shown in [Figure 4: see original paper]. The resulting signal exhibits noise with Vpp 80 mV, a significant improvement compared to the 300 mV noise Vpp observed for V2 in [Figure 3: see original paper]. This demonstrates that the integral circuit substantially improves the signal-to-noise ratio.

2.3 Filter Circuit

In traditional analog nuclear spectrum measurement systems, Sallen-Key (SK) circuits are commonly used to achieve Gaussian shaping of nuclear pulse signals, improving system signal-to-noise ratio by modifying pulse shape and amplitude [5]. To further enhance the energy resolution of the measured soft X-ray spectrum, a second-order SK low-pass active filter can be added after the differential-integral circuit. The unity-gain configuration is shown in Figure 5: see original paper. While C3 and C5 can theoretically be arbitrary, practical considerations regarding the cutoff frequency fc lead to selecting C5 based on its magnitude relationship with fc to avoid excessively large or small values for R5 and R6 [6].

Setting R5 = R6 = R and C5 = 2C3 = 2C yields a 4-element Butterworth SK circuit with frequency domain transfer function A(jω) = 1/(1 + j\$ $2RC + (j\ )^{\{2\}2C}\{2\}R\hat{}\{2\}$\$) and quality factor Q = 1/√2 0.707. In practice, the cutoff frequency of this Butterworth low-pass filter can be adjusted by changing R5 and C3 values to achieve optimal filtering performance and energy resolution.

3.1 Schematic Design

Based on the above analysis, the final schematic design for the soft X-ray signal shaping circuit is shown in [Figure 5: see original paper], prioritizing good energy resolution and circuit simplicity. The circuit consists of a differential stage, integral stage, and second-order low-pass filter. R7 is a 50 Ω termination resistor to mitigate transmission line T1 characteristic impedance effects. U1, U2, and U3 are integrated operational amplifier chips, C6 is an AC coupling capacitor, R8 is the load, and V1 is a custom excitation source. Using MATLAB to generate data for stepped sawtooth signals superimposed with Gaussian white noise of varying amplitudes, the V1 parameters can be modified to produce the signal shown in [Figure 6: see original paper] (right side shows zoomed view of circled region). Each step in this signal has a height of 21.83 mV, corresponding to the positive amplitude produced by 5.9 keV soft X-rays, with superimposed Gaussian white noise of adjustable Vpp. The signal resets every 2 V to simulate the level signal output from the reset-type charge-sensitive preamplifier in the soft X-ray detection system. When this excitation signal is input to the shaping circuit in [Figure 5: see original paper], simulation yields voltage data across load resistor R8 at the OUT node. Subsequent processing to extract peak information enables soft X-ray spectrum measurement and determination of energy resolution from the spectrum' s full width at half maximum (FWHM).

3.2.1 Low-Pass Filter Cutoff Frequency

As discussed in Section 2.3, the low-pass filter cutoff frequency can be adjusted by changing R5 and C3 values. To analyze the relationship between cutoff frequency and energy resolution (represented by FWHM since the 5.9 keV signal amplitude/peak position is fixed), the Gaussian white noise Vpp superimposed on excitation signal V1 was fixed at 3.7 mV—the step amplitude corresponding to the minimum measurable energy of 1 keV. By varying R5 and C3 values to change the cutoff frequency, multiple simulation runs yielded the results shown in Figure 7: see original paper. The horizontal axis represents the rise time of the output signal corresponding to different R5, C3 values (for analog signals, F3dB 0.35/Trise, where F3dB is the 3 dB bandwidth and Trise is the rise time). Considering the requirement of FWHM $\leq$ 133 eV and the fact that excessive rise time causes pulse pile-up at 10^5 cps count rates, the results in Figure 7: see original paper indicate that selecting Trise = 2000 ns with R5 = R6 = 128.6 kΩ, C3 = 5 pF, and C5 = 10 pF provides good filtering performance while meeting energy resolution requirements. Therefore, when signal noise Vpp does not exceed 3.7 mV, the shaping circuit can satisfy the requirement of energy resolution $\leq$ 133 eV @ 5.9 keV.

3.2.2 Integral Circuit Discharge Resistor

In the integral circuit, larger discharge resistor values produce smaller noise amplitudes, but excessively large resistors cause slow charge dissipation and resulting pile-up. Therefore, R2 value significantly impacts energy resolution and requires careful optimization. Increasing the noise Vpp superimposed on excitation signal V1 to 6 mV and varying R2 values, the relationship between energy resolution and R2 is shown by the solid line in Figure 7: see original paper, where the horizontal axis represents R2 resistance and the vertical axis represents FWHM at the spectral peak. The simulation confirms that increasing R2 reduces noise, but beyond a certain value, further increase causes more severe output pulse pile-up, degrading energy resolution. As shown in [Figure 8: see original paper], for two pulses with ~10 µs separation, using R2 = 1.1 MΩ produces more pronounced pile-up at 25 µs along the falling edge compared to R2 = 0.9 MΩ.

Combining results from Figure 7: see original paper and [Figure 8: see original paper], the simulation shows that R2 = 900 kΩ yields the narrowest spectral FWHM and best energy resolution, though still not meeting the $\leq$ 133 eV requirement.

3.2.3 Differential Circuit Series Resistor

In the differential circuit section of [Figure 5: see original paper], changing R1C4 values adjusts the first-stage gain, thereby affecting overall system signal-to-noise ratio. From Section 2.1.1, with the constraint R3C4 = R1C1 and considering that capacitance values have limited selection while resistors offer more flexibility, we set C1 = 1 pF and C4 = 100 pF, then vary R1 and R3 values to change the first-stage differential gain and observe its effect on energy resolution.

Increasing the superimposed noise Vpp to 7 mV, simulation results showing the relationship between FWHM and R3 resistance are plotted as the dashed line in Figure 7: see original paper. With noise Vpp at 7 mV, adjusting R1 and R3 values enables the system to meet the FWHM $\leq$ 133 eV requirement, demonstrating significant improvement compared to the R2 results. The optimal energy resolution occurs at R3 = 9 kΩ (with R1 = 900 kΩ).

4.1 Circuit Feasibility Analysis

Using the component parameters determined above in the circuit of [Figure 5: see original paper], with adjustments of R4 = 180 kΩ and C2 = 2 pF to ensure output signal amplitude within the ADC input range, the final output waveform using a sawtooth signal with superimposed Gaussian white noise (Vpp = 7 mV) as excitation source V1 is shown in [Figure 9: see original paper]. The left panel shows a 20 ms output waveform; because the input is a sawtooth wave that periodically resets, voltage transitions appear as negative peaks in the simulated output. The right panel shows a 1 ms segment where higher amplitude pulses result from two or more closely spaced or superimposed steps, related to the count rate detected by the SDD. The circuit successfully converts the stepped sawtooth signal from the reset-type charge-sensitive preamplifier into positive nuclear pulses of appropriate amplitude.

Processing the output signal to extract amplitude information yields the soft X-ray energy spectrum shown in [Figure 10: see original paper], where the horizontal axis represents extracted peak amplitudes of all nuclear pulses and the vertical axis shows the corresponding pulse counts. As a semiconductor detector, the SDD output voltage follows the relationship $U = K \cdot (e/W) \cdot (\Delta E/Cdet)$, where K is charge collection efficiency, e is electron charge, W is average energy to create an electron-hole pair, Cdet is detector capacitance, and ΔE is energy deposited by the particle. For X-rays where the photon range is less than the detector sensitive thickness, energy is fully collected (K = 1), making the output pulse amplitude linearly proportional to radiation energy [7]. The spectral peak' s horizontal coordinate corresponds to the pulse amplitude for 5.9 keV soft X-rays, enabling energy calibration and determination of soft X-ray energy from spectral amplitude. This confirms the feasibility of using this analog circuit in soft X-ray spectroscopy systems.

4.2 Noise Analysis

In the shaping circuit of [Figure 5: see original paper], gradually increasing the Vpp of Gaussian white noise superimposed on excitation source V1 and processing the simulated output waveforms yields the energy resolution results shown in [Figure 11: see original paper] for noise Vpp ranging from 3.7 to 10 mV. As input noise amplitude increases, the spectral FWHM broadens and energy resolution degrades. The results show that when noise Vpp $\leq$ 7 mV, the measured spectrum meets the requirement of energy resolution $\leq$ 133 eV @ 5.9 keV. Thus, the system requires the noise Vpp at the SDD output after the reset-type charge-sensitive preamplifier to be no higher than 7 mV, corresponding to $\mathrm{SNR} = 20\log_{10}(5.9\$\times\$3.7/7)$ 9.879 dB. Therefore, with preamplifier output signal SNR greater than 10 dB, the proposed shaping circuit can process the signal to achieve soft X-ray spectroscopy.

For stepped sawtooth signals from reset-type charge-sensitive preamplifiers in soft X-ray spectroscopy, direct digital processing after ADC conversion [8] demands high ADC sampling rate, resolution, and accuracy to maintain spectral resolution. This paper' s analog approach shapes and filters the preamplifier output to produce conventional nuclear pulses, with circuit simulation verifying feasibility. The discussed analog shaping circuit provides valuable reference for similar nuclear pulse signal processing applications.

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