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Shaping amplifier for soft X-ray spectrometer with a silicon drift detector

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Abstract. The paper presents a shaping amplifier developed to boost the count rate of a soft X-ray spectrometer AMPTEK based on a fast silicon drift detector (SDD). The amplifier differentiates step-like signals from the charge sensitive preamplifier of the SDD and gains the output signals for digitizing. The rise time of the output signals is reduced in regards with that of the AMPTEK shaping amplifier whereas the noise of these amplifiers is kept at the same level. The shorter rise time allows better resolution of closely overlapped output pulses and reduces the pile-up effects at high input count rates. The design of the amplifier is presented in the paper as well as its tests for noise, linearity and resolution of close overlapped pulses.

Keywords: shaping amplifier, VGA, PX-5, SDD

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Усилитель-формирователь для рентгеновского спектрометра с кремниевым дрейфовым детектором

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Аннотация. В статье описывается усилитель-формирователь, разработанный для увеличения скорости счета спектрометра мягкого рентгеновского излучения AMPTEK на основе быстрого кремниевого дрейфового детектора (SDD). Усилитель дифференцирует ступенчатые сигналы с зарядочувствительного предусилителя SDD и усиливает выходные сигналы для последующей оцифровки. Усилитель-формирователь обеспечивает меньшее время нарастания выходных сигналов по сравнению с усилителем-формирователем AMPTEK, в то время как шум этих усилителей остается на прежнем уровне. Уменьшение времени нарастания позволяет лучше разрешать наложенные выходные импульсы и уменьшает эффект возрастания общего уровня при высокой скорости счета входных сигналов. В статье представлена структура усилителя, а также его испытания на шум, линейность и разрешение наложенных импульсов.

Ключевые слова: усилитель-формирователь, VGA, PX-5, SDD

Финансирование: Проект и устройство усилителя-формирователя, описанные в

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Introduction

A soft X-ray spectrometer is developed in the Ioffe Institute for measurements of the Bremsstrahlung emission from plasma of the FT-2 tokamak [1] with the use an AMPTEK spectrometer based on a silicon drift detector (SDD) 70 mm^2 FASTSDD [2] and digital pulse processor (DPP) PX-5 [3]. The spectrometer is designed for high-resolution spectral measurements up to count rates 10^6 1/s in the energy range of photons from 0.5 to 30 keV. Higher energies are also detectable, but at less efficiency. A charge sensitive preamplifier integrated in the detector provides a step-like response on the detected photons with sensitivity 3.2 mV/keV. The detector window was collimated to 17 mm^2 for better energy resolution. The photon impact points are in the collimated depleted region are close to the anode and the rise time of the step signals vary in the narrowest range from 15 ns to 65 ns. The rise time of pulses here and further is measured between 20% and 80% levels to the pulse amplitude. The step amplitude ranges from 2 mV to 1.7 V in the energy measurement range. The step-like signals are shaped in the PX-5 module to pulses with rise time ~ 65 ns and falling exponential tail with characteristic time 3.2 μs. The shaped pulses are digitized at 80 MHz sampling rate and processed in PX-5. The selected rise time is a tradeoff between the highest count rate and the best energy resolution of the spectrometer.

The measurements in the FT-2 tokamak require higher count rate at the same energy resolution. For that, another shaping amplifier with shorter rise time and the same output noise is designed to provide better detection of overlapped pulses. The shaped output will be digitized and processed outside the PX-5 with the use of the same or special algorithms [4–6].

Design of shaping amplifier

The schematic layout of the amplifier is presented in Fig. 1. The 1 kΩ input of the amplifier is connected to the output of the charge sensitive preamplifier of the detector. The input signal is doubled by operation amplifier DA1, differentiated in RC circuit with switchable resistors (R2...R5) and buffered by DA2. The RC circuit determines the exponential falling time of the output pulses in the range from 2 μs to 17 μs. Resistors (R2...R5) are grounded through analog switches (S1...S4) to avoid extra inductance and capacitance in the circuit. The analog switches are installed on the printed circuit board and activated by toggle switches (T1...T4) on the case of the device. The buffered signal splits in channel A and channel B having different gains to expand the measurement range of photon energies. The channels have variable gain amplifiers (VGA) DA3 and DA4. The gain in channel A and B varies from 5 to 40 and from 1 to 6 correspondingly. The gain is controlled by multi-turn potentiometers R6 and R7 connected to the reference voltage 1.225 V. Amplifiers DA5 and DA6 doubles the signals and match them to the 50 Ω inputs of digitizers.

The gain of channel A is set in the range from 10 to 80 for measurements of photon energies up to 50 keV. The gain of channel B is set from 2 to 12 for measurements of photons with energies more than 30 keV. The output pulses are formed with the least rise time providing the output noise ~ 45 eV at the level of the shaping amplifier in PX-5 module.

Test of the shaping amplifier

The amplifier has been tested with FASTSDD detector of AMPTEK and a ^{55}Fe isotope source radiating at ~ 25000 photon/s on the detector area. A generator of rectangular pulses with a sharp

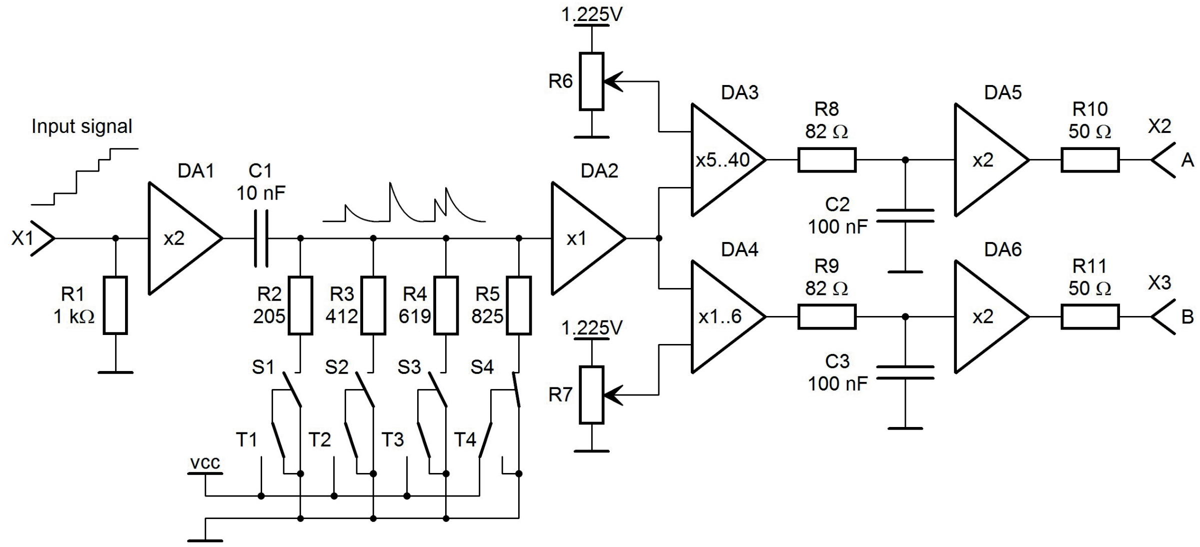

Fig. 1. Schematic layout of the amplifier

rise time of 20 ns and of switchable accurate standard amplitudes was also used for testing the amplifier. The output signals of the amplifier and PX-5 were recorded by an ADC at 250 MHz, 14 bits resolution produced by InSys [7] or a digital scope Agilent Technologies MSO9440A with 10 bits resolution and analog bandwidth 4 GHz. The recorded signals were smoothed with a digital low pass RC filter with a cut-off frequency 40 MHz. The filter dumps the noise dominated part of the spectra and does not affect the spectrum and shape of the output pulses from the PX-5 and amplifier units.

Output noises of the PX-5 and amplifier were measured in the whole gain range with the use of InSys ADC 250 MHz and plotted in Fig. 2, *a*, in eV units. Noise of the PX-5 amplifier increases from 45 eV to 130 eV when its gain reduces from 12 to 2. Channel B of the amplifier shows a similar behavior with the excess noise factor ~ 1.5. In spite of higher absolute values, the relative noise in channel B is much less than 1% because the channel is designed for a high energy range 30–500 keV. Channel A exhibits lower absolute noise from 40 eV to 55 eV.

Amplitude spectra of the noises and output signals of PX-5 and amplifier are shown in Fig. 2, *b*. The spectra decay linearly with the frequency up to 2.4 MHz and 6.4 MHz for PX-5 and amplifier signals correspondingly. These cut-offs are inversely proportional to the rise time of the output pulses [5].

The front edges of the PX-5 and amplifier pulses along with the step-like detector signals measured with the digital scope are presented in Fig. 3, *a*. The shown detector response has the rise time 35 ns which is the mean rise time of the steps. The detector noise is 1.2 mV or 380 eV rms. The response pulses from PX-5 and amplifier shown by dashed traces have the rise times 83 ns

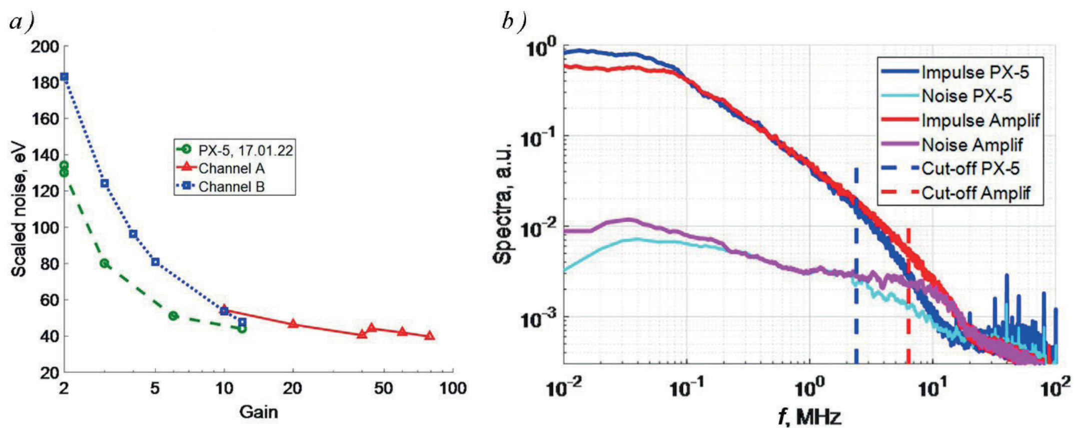

Fig. 2. Diagrams of output noise of PX-5 and amplifier on the gain (*a*), amplitude spectra of noise and signals (*b*)

and 46 ns correspondingly. The noise of the both responses is 45 eV rms. The amplifier pulse was recorded from channel A at gain 20 and reduced to the PX-5 pulse with coefficient 0.15. A solid green trace represents a step pulse from the pulse generator with a shorter rise time 19 ns and less noise 25 eV. This pulse is shaped to a pulse represented with a green dotted trace with rise time 34 ns and noise 23 eV rms. These low noises generator with variable amplitudes is used for calibration of the spectrometer in the whole energy range.

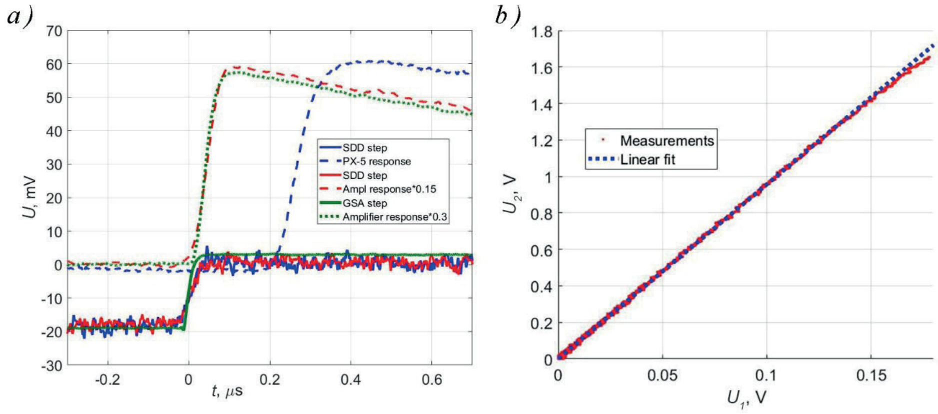

Fig. 3. Front edges of impulse responses on a photon of 5.9 keV (*a*), linearity of amplifier (*b*)

The output pulses of the amplifier maintain the shape and linearity in a wide range of output voltage. Linearity of the amplifier is shown in Fig. 3, *b*, by the dependence between the instant voltages of two synchronized output pulses U_1 and U_2 measured at the minimal and maximal gains in channel A, red dots. The measurements correspond to the linear fit shown by a dashed blue line up to 1.5 V of the output voltage. The signals are saturated at 1.8 V.

Low noise and short rising time of the amplifier provide better resolution of two overlapped pulses. This advantage is illustrated in Fig. 4, *a*, which shows two overlaps of two identical pulses. The first pulses in the overlaps were taken from PX-5 and amplifier outputs with noises and normalized to their amplitudes. The normalized pulses were delayed by 100 ns and sum to the first ones. The pulses from PX-5 and amplifier are shown in blue and red solid traces. The both overlaps do not have any peaks corresponding to the single pulses. The peaks appear in the overlaps after digital filtering. Usually, trapezoidal filtering [8] is applied in pulse detection algorithms [4].

The overlapped signals of PX-5 and amplifier filtered by a trapezoidal filter with a peaking time 50 ns and flat top 20 ns are plotted in blue and red dashed traces. The peaking time 50 ns is used in the fast channel of DPP PX-5. The trapezoidal pulse from PX-5 has an asymmetrical shape with an extended tail, whereas the shape of the trapezoidal pulse from the amplifier keeps a symmetrical form. This difference is accounted by a larger rise time of the PX-5 pulses [5].

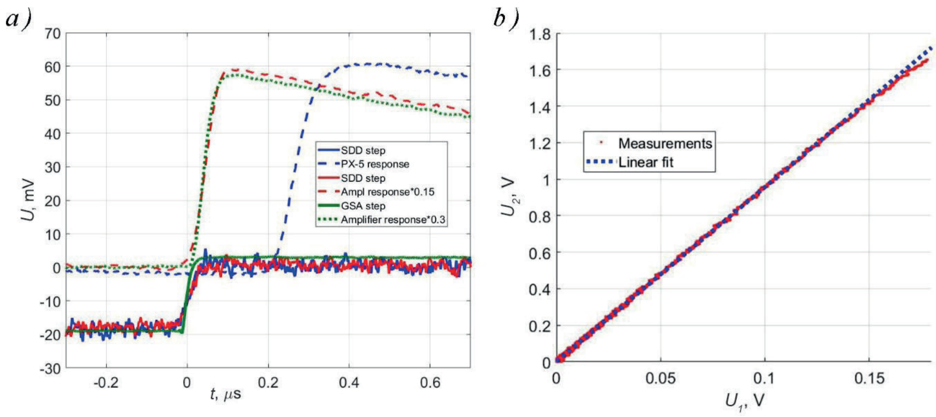

Fig. 4. Overlapped pulses from PX-5 and amplifier and overlapped trapezoidal pulses (*a*), peak amplitudes of two overlapped trapezoidal pulses (*b*)

The peak amplitudes of two overlapped trapezoidal pulses depend on the lag time between them, see Fig. 4, *b*. At large lags, the peaks from overlapped trapezoidal pulses are detected with biasing-free unit amplitudes. At lags shorter than 200 ns the amplitude of second peaks from PX-5 gets higher than the first one because of asymmetry of the trapezoidal pulses. The difference in the peak amplitudes increases while the lag is decreasing to 80 ns. At this lag the only peak remains in the overlapped signal. A blue dashed vertical line defines a threshold when the deepness of the valley between two peaks is less than 10% of the peak height.

Thus, two peaks of identical trapezoidal pulses from PX-5 are detected with their correct amplitudes while the lag is greater than ~ 170 ns. The amplitude of the second peak is biasing up to 15% when lag is decreasing to 90 ns. On the other hand, two peaks of the trapezoidal pulses from the amplifier are detected without biasing down to ~ 80 ns lag, which is close to the threshold lag of detection of overlapped pulses from the amplifier.

Conclusion

The designed shaping amplifier allows better resolution of overlapped impulse responses of Silicon Drift Detector FASTSDD than does Digital Pulse Processor PX-5 of AMPTEK Inc. This advantage is provided by a shorter rise time of output pulses and similar noise of the amplifier in regards with those of the internal amplifier in PX-5 module of AMPTEK spectrometer. The rise time affects significantly the distortion of trapezoidal pulses which restricts the least lag between the detected pulses.

The developed amplifier provides two parallel outputs with identical pulse forms and independently controlled gains. One channel with higher gain intentionally measures spectra in lower energy region up to 50 keV. The second channel with lower gain operates in a higher energy region up to 500 keV.

Better resolution of overlapped pulses provided by the shaping amplifier allows a higher count rate of the spectrometer. This possibility is presented, discussed and tested in [9].

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