Development of readout electronics for silicon photomultiplier detectors

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Schemes for optimal readout of signals from silicon detectors are proposed. A method of increasing the detecting area by simple summation of signals from detectors and a readout circuit with minimum power consumption are proposed. Detector pixels based on MicroFJ-60035 silicon photomultipliers for two detector clusters consisting of 28 pixels were created using the developed schemes. The pixel tests were carried out, showing the possibility to register both single photons and high intensity photon streams. A prototype module of the detector camera based on MicroFC-60035 silicon photomultipliers has been designed and developed.

Keywords: detectors, silicon photomultipliers, readout electronics, signal acquisition circuit.

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Currently, silicon photomultipliers (SiPMs) are widely used in a number of tasks for recording light pulses in many science and technology areas, including recording of single photons. They turn to be more effective compared to the vacuum photomultipliers [1]. At the same time, SiPMs, due to their high speed, can also be used to record intense photon fluxes, which necessitated the development of fast readout electronics for silicon photomultipliers.

In Ioffe Physical and Technical Institute a project of a unique terrestrial Cherenkov gamma observatory ALEGRO has been developed for some years [2,3]. Currently some studies are being carried out aimed at development of new SiPM-based detector clusters of J-series (MicroFJ-60035) and C-series based detector camera prototype (MicroFC-60035) for recording of Cherenkov flares with an intensity from single photons to several thousand photons. The developed equipment is tested on the existing Cherenkov telescope TAIGA-IACT [4,5].

The aforementioned SiPMs are distinguished by a fast yield, where the signal duration is about 3 ns, while the pulse edge duration standing for the time of charge collection from the triggered avalanche photodiodes of the detector, is less than 1 ns. In order for the pulse duration at the preamplifier input to be commensurate with the signal duration from the fast output, it is necessary to ensure a time constant at the same level (about 1 ns). The time constant at that is equal to the production of the pre-amplifier input resistance R_{IN} by the capacitance of the fast output C_{FA} which is equal 48 pF and 160 pF for MicroFC-60035 and MicroFJ-60035, respectively.

Thus, the input resistance R_{IN} shall be within $6-18\,\Omega$. Obviously, with such a resistance, the amplitude of the signal generated by SiPM current pulses from single photons (about tens of μA) will be small. However, a small time constant can be obtained due to the low input resistance using an active element — current repeater.

The most simple version of a current repeater — is a base-coupled logic circuit, where the input resistance of a stage is defined as a ratio of temperature potential φ_T, equal 26 mV at 25 °C to the emitter current I_e. Having taken the appropriate current by formula $R_{IN} = \varphi_T/I_e$ we may obtain R_{IN} at a level of $5-10\,\Omega$, thus providing the small time constant of the pulse from the „fast" output.

When creating pixels for new detector clusters, it was necessary to provide a detection area equivalent to the area of vacuum photomultipliers used in the existing telescope TAIGA-IACT.

In paper [6] a detecting pixel capable of coping with this task was outlined. Each pixel contains a Winston cone that provides the light focusing on four SiPMs, and the signals from each of them are picked up by preamps. Further digitization and signal processing is carried out on the recording board. To minimize the number of recording channels, a signal adder from four preamps is used. The disadvantage of the circuit described in jcite6 is the high power consumption (1.5W) caused by the large number of operational amplifiers.

At the same time, given that a large number of pixels are used in the telescope's camera, the total power consumption becomes unacceptable for the existing design of the detector camera inTAIGA-IACT telescope. To solve this problem, an alternative logic of signals readout from four SiPMs was developed and implemented, providing significantly lower consumption (0.45 W) with the same parameters (Fig. 1). The key point in this logic was the option of summing current repeater signals. For this purpose, the transistor collectors in the current repeaters on the detector board were interconnected.

This solution allows using one preamp circuit to capture a signal from four SiPMs at once. As a result, a detector circuit on four MicroFJ-60035 and a preamp circuit containing only two operational amplifiers instead of the nine from paper [6] were developed.

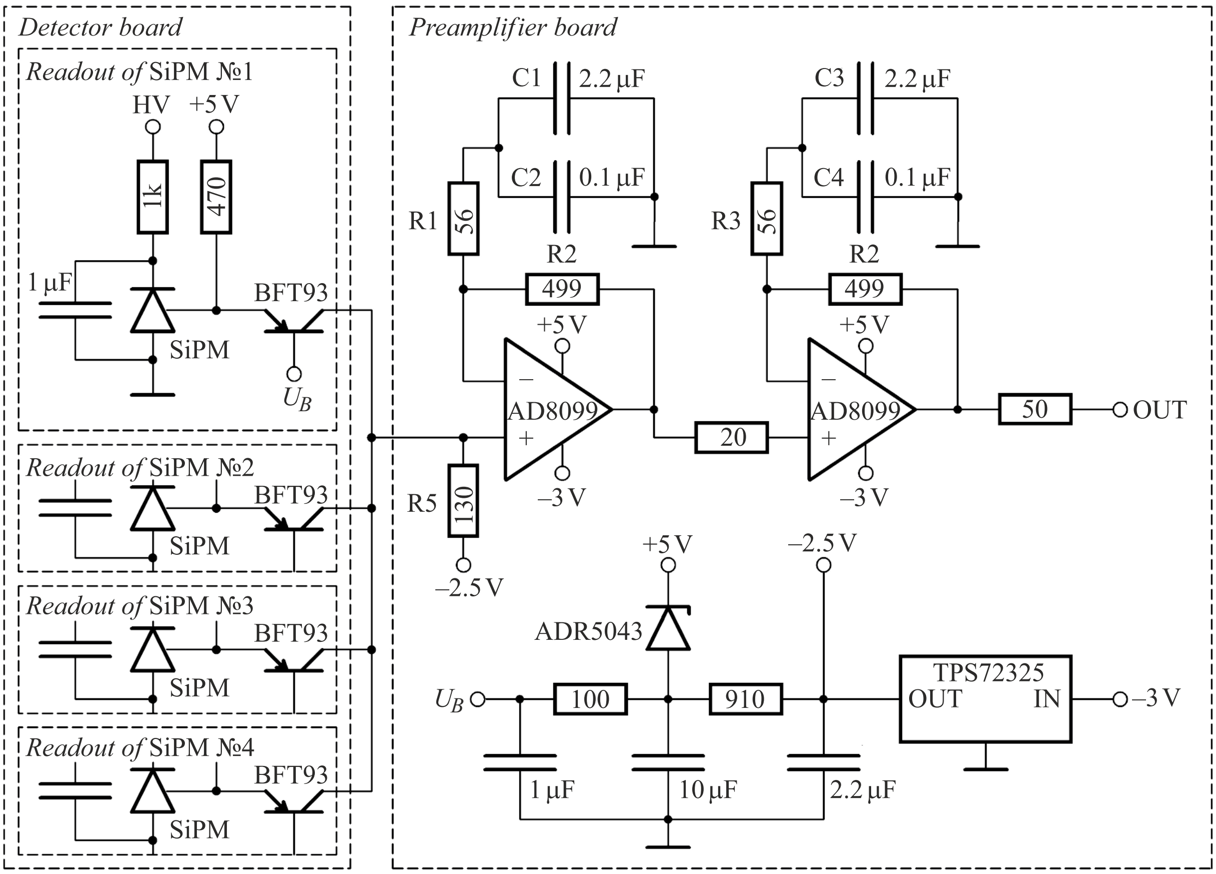

Figure 1. Simplified electric circuit of pixel.

The simplified circuit of pixel is presented in Fig. 1. The signals from the fast detector outputs are summed by connecting the collectors of BFT93 transistors. However, the output capacities of the current repeaters are also summed up. However, due to their insignificance (about 1 pF) and the small input impedance of R5 preamp, equal to 130 Ω, this does not significantly affect the time parameters of the circuit.

When summing the detector signals, the quiescent currents of the input repeaters are also summed, the sum of which is 20 mA. This leads to the need to shift the input resistor R5, which converts current into voltage, from „ground" to negative voltage (−2.5 V). Considering this, the voltage drop across R5 will be 2.6 V, as a result of which a constant level bias (about 100 mV) is formed at the preamplifier input, which is a „pedestal" for the further recording logic.

The constant level at the pre-amplifier input is repeated at its output, since the amplification stages have a gain factor of 1 for constant voltage. However, at high frequencies, each stage has a gain factor close to 10, which is provided by the circuits R1-R2-C1-C2 and R3-R4-C3-C4. The amplification stages are based on AD8099 broadband operational amplifiers with voltage feedback, which are characterized by an ultra-low voltage noise density ($0.95\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$) combined with a high rise rate (1350 V/μs). In the circuit shown in Fig.1, a precision reference voltage source ADR5043 is used to stabilize the base potential (U_B) of the detector's transistor current repeaters, as well as an integrated negative voltage stabilizer TPS72325 at −2.5,V. In combination with the appropriate stabilization of the operational amplifier power circuits (+5 V and −2.5 V), the reference voltage source maintains a constant potential at the transistor bases.

Structurally, the SiPM signal readout circuit is made as two printed circuit boards: detector board and preamplifier board. The boards are soldered together at a right angle and form a pixel together with the housing (Fig. 2). The detector board contains four SiPMs and elements shown in Fig. 1 for the detector board. The pixel body is made in the form of a cylindrical aluminum tube with internal threads at the ends, into which threaded rings are screwed fixing soldered boards inside the body.

Figure 3 shows an oscillograph record of a dark count signal from a pixel with an amplitude of 4 photoelectrons (4 triggered microcells) when there's an overvoltage 4 V of the detectors. The pulse shape is symmetrical, the front and back have a duration of about 2 ns, the pulse width at half maximum is 4 ns.

Based on the developed circuits, detector pixels based on SiPMMicroFJ-60035 were created for two detector clusters

Figure 2. View of a pixel of the new detector cluster in the analysis.

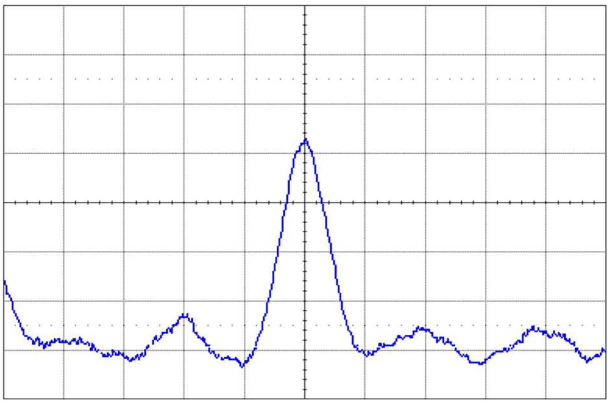

Figure 3. An oscilloscope of a dark count signal from a pixel with an amplitude of 4 photoelectrons.

consisting of 28 pixels each. Laboratory tests of detector clusters were carried out, which showed the possibility of detecting both, single photons and high-intensity photons [7]. One detector cluster was successfully tested in the operating telescope TAIGA-IACT of TAIGA astrophysical site during 2022 summer-autumn observation season. The second detector cluster arrived at the test site along with a specially designed cluster controller for future joint testing of ALEGRO camera prototype. An experimental module of ALEGRO detector camera prototype based on a silicon photomultiplier was also developed and fabricated MicroFC-60035.

Conflict of interest

The authors declare that they have no conflict of interest

References

[1] I. Ivanov. Science magazine „Fotonika“, **6**, 70 (2015) (in Russian).
https://photonics.su/files/article_pdf/4/article_4989_578.pdf

[2] A.M. Bykov, F.A. Aharonian, A.M. Krassilchtchikov, E.E. Kholupenko, P.N. Aruev, D.A. Baiko, A.A. Bogdanov, G.I. Vasilyev, V.V. Zabrodskii, S.V. Troitsky, Yu.V. Tuboltsev, A.A. Kozhberov, K.P. Levenfish, Yu.V. Chichagov. Tech. Phys., **62** (6), 819 (2017). http://doi.org/10.1134/S106378421706007X

[3] E.E. Kholupenko, A.M. Bykov, F.A. Aharonyan, G.I. Vasiliev, A.M. Krassilchtchikov, P.N. Aruev, V.V. Zabrodskii, A.V. Nikolaev. Tech. Phys., **63** (11), 1603 (2018).
http://doi.org/10.1134/S1063784218110154

[4] L.A. Kuzmichev, I.I. Astapov, P.A. Bezyazeekov, M. Blank, E.A. Bonvech, A.N. Borodin, M. Brueckner, N.M. Budnev, A.V. Bulan, D.V. Chernov, A. Chiavassa, A.N. Dyachok, A.R. Gafarov, A.Yu. Garmash, V.M. Grebenyuk, O.A. Gress, T.I. Gress, A.A. Grinyuk, O.G. Grishin, D. Horns, A.L. Ivanova, N.N. Kalmykov, V.V. Kindin, S.N. Kiryuhin, R.P. Kokoulin, K.G. Kompaniets, E.E. Korosteleva, V.A. Kozhin, E.A. Kravchenko, A.P. Kryukov, A.A. Lagutin, M.V. Lavrova, Yu. Lemeshev, B.K. Lubsandorzhiev, N.B. Lubsandorzhiev, A.D. Lukanov, D. Lukyantsev, R.R. Mirgazov, R. Mirzoyan, R.D. Monkhoev, E.A. Osipova, A.L. Pakhorukov, A. Pan, L.V. Pankov, A.D. Panov, A.A. Petrukhin, D.A. Podgrudkov, V.A. Poleschuk, E.G. Popova, A. Porelli, E.B. Postnikov, V.V. Prosin, V.S. Ptuskin, A.A. Pushnin, R.I. Raikin, A. Razumov, E. Rjabov, G.I. Rubtsov, Y.I. Sagan, V.S. Samoliga, A.Yu. Sidorenkov, A.A. Silaev, A.A. Silaev, Jr., A.V. Skurikhin, M. Slunecka, A.V. Sokolov, Y. Suvorkin, L.G. Sveshnikova, V.A. Tabolenko, A.B. Tanaev, B.A. Tarashansky, M. Ternovoy, L.G. Tkachev, M. Tluczykont, N. Ushakov, A. Vaidyanathan, P.A. Volchugov, N.V. Volkov, D. Voronin, R. Wischnewski, I.I. Yashin, A.V. Zagorodnikov, D.P. Zhurov. Phys. Atomic Nuclei, **84** (6), 966 (2021).
http://doi.org/10.1134/S1063778821130172

[5] N.M. Budnev, I.I. Astapov, P.A. Bezyazeekov, A.N. Borodin, R. Wischnewski, A.Yu. Garmash, A.R. Gafarov, N.V. Gorbunov, V.M. Grebenyuk, O.A. Gress, T.I. Gress, A.A. Grinyuk, O.G. Grishin, A.N. Dyachok, D.P. Zhurov, A.V. Zagorodnikov, V.L. Zurbanov, A.L. Ivanova, Yu.A. Kazarina, N.N. Kalmykov, N.I. Karpov, V.V. Kindin, P.S. Kirilenko, S.N. Kiryuhin, V.A. Kozhin, R.P. Kokoulin, K.G. Kompaniets, E.E. Korosteleva, E.A. Kravchenko, L.A. Kuzmichev, M. Kunnas, A. Chiavassa, A.A. Lagutin, V.V. Lenok, B.K. Lubsandorzhiev, N.B. Lubsandorzhiev, R.R. Mirgazov, R. Mirzoyan, R.D. Monkhoev, R. Nakhtigal, E.A. Osipova, M.I. Panasyuk, L.V. Pankov, A.L. Pakhorukov, A.A. Petrukhin, V.A. Poleschuk, M. Popescu, E.G. Popova, A. Porelli, E.B. Postnikov, V.V. Prosin, V.S. Ptuskin, A.A. Pushnin, R.I. Raikin, G.I. Rubtsov, Y.I. Sagan, V.S. Samoliga, L.G. Sveshnikova, A.Yu. Sidorenkov, A.A. Silaev, A.A. Silaev, A.V. Skurikhin, M. Slunecka, A.V. Sokolov, V.P. Sulakov, V.A. Tabolenko, A.B. Tanaev, B.A. Tarashansky, L.G. Tkachev, A.V. Tkachenko, M. Tluczykont, O.L. Fedorov, D. Horns, C. Spiering, I.I. Yashin. Bull. Russ. Acad. Sci. Phys., 83 (8), 951 (2019). http://doi.org/10.3103/S1062873819080100

[6] A.A. Bogdanov, Yu.V. Tuboltsev, Yu.V. Chichagov, A.M. Krassilchtchikov. J. Phys.: Conf. Ser., **2103**, 012026 (2021). http://doi.org/10.1088/1742-6596/2103/1/012026
[7] A.A. Bogdanov, G.A. Repman1, Yu.V. Tuboltsev, Yu.V. Chichagov, E.E. Kholupenko, A.M. Krassilchtchikov. J. Phys. Mathemat., **16** (1.2), 410 (2023). https://doi.org/10.18721/JPM.161.262

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