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An ASIC Front-End for Fluorescence and Cherenkov light detection with SiPM for space and ground applications

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Abstract

Astroparticle and High Energy Astrophysics space missions measuring extensive air showers produced by cosmic rays and neutrinos in atmosphere require detection of very faint and intense ultraviolet and visible light. Characteristics of the new generation of SiPM (Silicon PhotoMultiplier) are potentially right for this purpose. Their high intrinsic gain, low power consumption, low weight and robustness against accidental exposure to light are particularly important for spaceborn multipixels imaging cameras. Their high-performance detection makes them promising for photon counting, where extreme photodetector sensitivity is needed, as well as for charge integration, where the total amount of charge in the signal is required. The capability to operate SiPM contemporarily in photon counting and in charge integration is strictly dependent indeed by the design of the front-end electronics (FEE). In this context, the challenge is to find the right balance and a feasible solution for managing SiPM with a FEE to be able to work, contemporarily and efficiently, in photon counting and charge integration.

Keywords: Cosmic Rays, Gamma Rays, Neutrinos, SiPM, ASIC, Cherenkov, Fluorescence

1. Introduction

In the last years there were many experiments devoted to the study of energetic messangers from the Universe, first af all the Cosmic Rays and the Gamma Rays.

For the Cosmic Rays, especially the ones which have an energy greather than $10^{19}\ eV$, the flux of events is very low ($\sim 1\ particle\ /\ 100\ km^2\ /\ year$ for Cosmic Rays with an energy greater than $10^{20}\ eV$) and so the only way to have a reasonable statistic is to have a very large collecting area; for this reason, the next step after the biggest existing Cosmic Rays' observatory (Auger Observatory with its $3000\ km^2$) is to look downward at the dark earth atmosphere from an observatory placed in orbit. To achieve this gol the most important missions proposed in the past were EUSO (Extreme Universe Space Observatory) and KLYPVE (which Russian acronym means Extreme Energy Cosmic Rays); since these two projects have not yet been realized, there were some pathfinder missions and balloon flights related to them, to better understand the physics and the technological challenges behind these experiments. Talking about the balloons, we must start from the BaBy one [1], that flew three times from Trapani-Milo ASI base; and continue with the EUSO related ones, from the EUSO-Balloon first flight to the Super Pressure Balloon, EUSO-SPB1, that will be followed by EUSO-SPB2, a future mission approved by NASA, that will fly on 2022. Among the pathfinders, we must remember Mini-EUSO, that was launched on August 2019 and is ongoing on the Russian module of the International Space Station (ISS); and K-EUSO, that will be launched at the end of 2022 and will take place on the Russian module of the ISS too. We can't forget TUS (Tracking Ultraviolet Setup), a satellite launched on April 2016 for the same purposes. The next years will be leaded by two big projects that will be devoted to the detection of UHECRs: EUSO and POEMMA (Probe of Extreme Multi-Messenger Astrophysics). These projects will not search only energetic cosmic rays, but other rare events like neutrinos.

For energies up to a few hundred TeV it is possible to use ground-based telescopes such as Cherenkov telescopes, which are dedicated to the detection of gamma rays. Some of them are: MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope), H.E.S.S. (High Energy Stereoscopic System) and VERITAS (Very Energetic Radiation Imaging Telescope Array System), but the next years will be leaded by the CTA (Cherenkov Telescope

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Array) observatory, that will be made by different types of telescopes to search the gamma universe from 20 GeV to 300 TeV.

2. Physics

The space based experiments mentioned in ¶ 1 will be devoted to the search of Ultra High Energy Cosmic Rays (UHECRs), neutrinos and gamma rays. Some of them are indicated in Fig. 1.

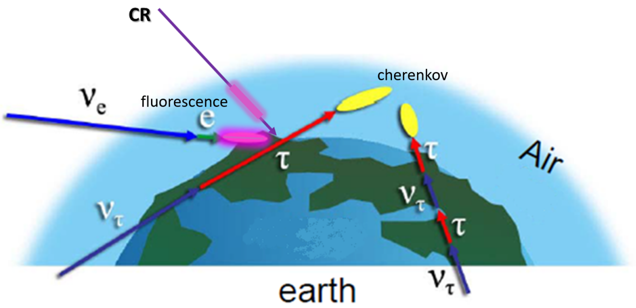


Figure 1: Artistic representation of some particles that can produce fluorescence and Cherenkov light when they interact with the Earth atmosphere.

The cosmic rays are high-energy radiation which originate from the outer space and move at nearly the speed of light. Some of them reach the Earth and, upon impact with the atmosphere, they can produce cascades of secondary particles that sometimes reach the surface: these cascades are called Extensive Air Showers (EASs). One of the key feature of the cosmic rays is the energy spectrum which covers 14 orders of magnitude in energy and 32 orders of magnitude in flux: this leads to a low statistics at higher energies, so the highest ones are the less known. The mentioned space based experiments will especially look for UHECRs, which have an energy in the region of EeV and more ($1\ EeV = 10^{18}\ eV$). The origin and composition of UHECRs remain a challenging enigma of particle astrophysics, but their macroscopic energies likely links their origin to the most energetic processes in the Universe and possibly testify physics not yet discovered. Regardless of its composition, we know that a primary cosmic ray strikes atoms nuclei in the air, so it produces energetic hadrons and these ones decay into other ionized particles and electromagnetic radiation, so an EAS is made of different components, three above all: the hadronic one, the muonic one and the electromagnetic one. The last one constitutes about the 90% of the total and is made of electrons, positrons and photons. In addition we must say that the EASs produce Cherenkov and fluorescence light.

The neutrinos are fermions (elementary particles) that interact only through the weak subatomic force and gravity. They are electrically neutral and their rest mass is much smaller than that of the other known elementary particles. Since they do not participate in the strong interaction, the weak force has a very short range and the gravitational interaction is extremely weak, the neutrinos typically pass through normal matter unimpeded and undetected. Weak interactions create neutrinos in one of three leptonic flavors: electron neutrinos, muon neutrinos or tau neutrinos, in association with the corresponding charged lepton. We are very interested in the search for tau neutrinos, coming from the space, because a detection could shed new light on the open questions of this research field, but the high energy neutrinos have a very low interaction cross section and for this reason it is very difficult to detect them. The space based telescopes discussed before could observe astrophysical and cosmogenic neutrinos combining Cherenkov and Fluorescence measurements, detecting deeply penetrating horizontal showers initiated by all flavors of EeV neutrinos in the atmosphere and the signal produced by tau neutrinos from $10^7\ GeV$ (where astrophysical neutrinos are expected) to $10^{10}\ GeV$ (where cosmogenic neutrinos can be discovered).

The gamma radiation is a penetrating electromagnetic radiation emitted by atomic nuclei. It consists of the shortest wavelength electromagnetic waves and so imparts the highest photon energy. In astrophysics, gamma rays with photon energies above 100 keV are the subject of gamma ray astronomy. For energies above a few hundred GeV, as explained in Catalano *et al.*, 2019 [4], the observation of primary gamma rays from space with satellites or stratospheric balloons becomes inefficient, so that a direct measurement is impossible due to the limitation of the detection surface necessary to intercept primary gamma rays, whose flux is greatly reduced as the energy increases. We then rely on an indirect measurement, that is the detection of secondary particles produced by the interaction of gamma rays with the Earth's atmosphere. Our detector is now the atmosphere, that simultaneously performs the function of absorber and converter. In the atmosphere, primary charged particles and gamma rays coming from the outer space, interact with the atoms of the air, producing a cascade of ionized particles and electromagnetic radiation, which in turn create other secondary particles and electromagnetic radiation and so on, creating the EAS.

The secondary charged particles give rise to the well-known phenomenon of Cherenkov light production that occurs when a charged particle (like an electron) passes through a dielectric medium, the air in our case, at a speed higher than the speed of light in that medium. The charged particles polarize the air molecules, which then quickly return to their fundamental state, emitting photons in the direction of travel of the charged particles and producing a feeble (a few ten photons per meter) and very short (a few ns) light emission in the ultraviolet and visible wavelengths. The contribution in Cherenkov photons of all the charged particles of an EAS in its evolution in the atmosphere manifests itself, at an observational level, as a cone of light with the vertex at the point of first interaction of the primary particle with the air and the radius of the cone circumference of about 120 m. This light can only be detected during the night by means of telescopes with large optical collecting surfaces and with fast and very sensitive multi-pixel cameras. The use of several telescopes, conveniently positioned, which operate simultaneously, improves the performance in energy resolution and the position accuracy of the gamma source observed in the sky, concurrently increasing the statistics of the number of detected events.

Fluorescence light refers to the process in which the atoms absorb photons of a wavelength and emit photons at a longer wavelenth. The ionizing component of EASs can induce such fluorescent radiation from the excitation of molecules of nitrogen in the air. A part of this excitation energy is then emitted in the form of visible and ultraviolet radiation. The photons produced in the air thanks to the fluorescence phenomenon are less than the Cherenkov radiation ones and the efficiency is low, but they have the advantage of being emitted isotropically (while the Cherenkov light is emitted in a beamed cone by secondary charged particles) and have an absorption coefficient relatively low in the atmosphere; furthermore it has a track progression that lasts tens of microseconds, a long time if compared with the Cherenkov one.

3. CITIROC

In the context of the CTA project, INAF (Istituto Nazionale di AstroFisica) contributes from the beginning with the design, development and construction of a prototype telescope, ASTRI-Horn [6], which will now be the starting point for the ASTRI mini-array, consisting of 9 ASTRI telescopes similar to the current prototype. The ASTRI core is the camera [2], designed to capture and record fast pulses of Cherenkov light during the night, in the wavelength range of $300-600$ *nm*. To detect the phenomena treated in ¶ 2, SiPM were chosen, thanks to their characteristics, as the high intrinsic gain, low power consumption, low weight and robustness against accidental exposure to light. The SiPM reading electronics [7] is quite different from the one used in all other Cherenkov telescopes. As mentioned before, the Cherenkov light signal is of very low intensity with a duration of only a few ns. The camera, therefore, must have a high sensitivity and a very high speed acquiring the flashes of Cherenkov light. In order to have the required performance in terms of sensitivity and speed of acquisition, upon INAF suggestion and request, the French company Weeroc, which recognizes INAF for intellectual property, designed and marketed an ASIC (Application-Specific Integrated Circuit), named CITIROC (Cherenkov Imaging Telescope Integrated Read Out Chip) (Fleury *et al.*, 2013 [5]), whose block scheme is shown in Fig. 2 and whose characteristics are listed in Fig. 3 and detailed in the datasheet [8]. Here we will only talk about the main ones.

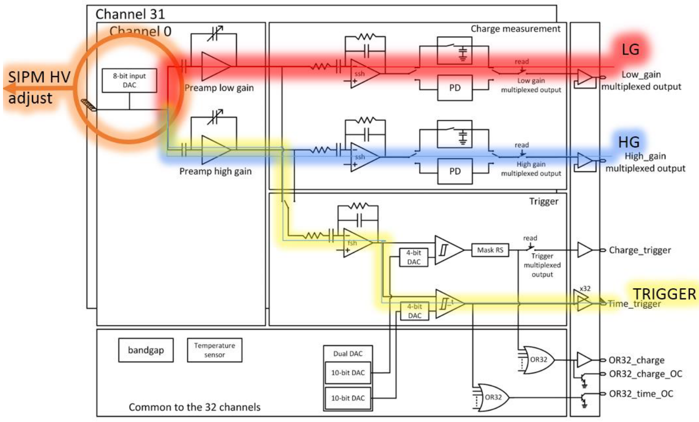
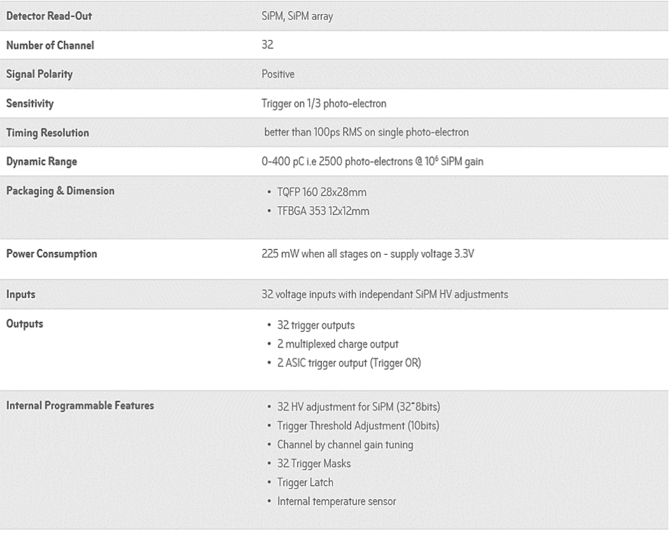


Figure 2: General block scheme of the CITIROC ASIC. Colored paths identify the Low Gain, High Gain and Trigger chains.



Detector Read-Out	SiPM, SiPM array
Number of Channel	32
Signal Polarity	Positive
Sensitivity	Trigger on 1/3 photo-electron
Timing Resolution	better than 100ps RMS on single photo-electron
Dynamic Range	0-400 pC i.e 2500 photo-electrons @ 10^6 SiPM gain
Packaging & Dimension	• TQFP 160 28x28mm • TFBGA 353 12x12mm
Power Consumption	225 mW when all stages on - supply voltage 3.3V
Inputs	32 voltage inputs with independant SiPM HV adjustments
Outputs	• 32 trigger outputs • 2 multiplexed charge output • 2 ASIC trigger output (Trigger OR)
Internal Programmable Features	• 32 HV adjustment for SiPM (32*8bits) • Trigger Threshold Adjustment (10bits) • Channel by channel gain tuning • 32 Trigger Masks • Trigger Latch • Internal temperature sensor

Figure 3: CIRIROC ASIC main characteristics.

CITIROC 1A (an improved version of the first one) is a 32-channel front-end ASIC designed to readout SiPM (and for this reason the FEE is equipped with two chips); it allows triggering down to 1/3 pe (photo electron) and provides the charge measurement with a good noise rejection. It outputs the 32-channel triggers with a high accuracy (better than 100 ps). An adjustment of the SiPM high-voltage is possible using a channel-by-channel DAC connected to the ASIC inputs. This allows a fine SiPM gain adjustment at the system level to correct for the gain non-uniformity of SiPM pixels. Timing measurement better than 100 ps RMS jitter is possible along with 1% linearity energy measurement up to 2500 pe. The power consumption is about 7 mW/channel with all features ON.

Going into detail, as explained in Catalano *et al.*, 2018 [3] and shown in Fig. 2, each CITIROC is characterized by separate chains for high gain (HG), low gain (LG) and trigger outputs. Each CITIROC channel implements an 8-bit DAC for SiPM gain adjustment. The pulse generated by the SiPM is processed by the AC-coupled CITIROC electronic channel. For example, for the ASTRI-Horn telescope, it is amplified by means of two programmable preamplifiers (a nominal Gain = 3.3 for LG and a nominal Gain = 66.6 for HG were chosen) and then shaped (nominal shaping time = 25 ns) with two shaper circuits (LG and HG) respectively; the gain values have been chosen to obtain a dynamic range from 0 to about 60 pe for the HG channel and from 0 to about 1300 pe for the LG channel. A bipolar fast shaper (FSH in Fig. 2) connected to the high gain preamplifier produces a fast signal ($\sim 15\ ns$ shaping time) that is connected to a discriminator with a 10 bits-DAC programmable threshold. The output of the discriminator gives a digital signal (trigger) if the input signal exceeds the threshold level. The peak detector or single channel analyzer (track&hold mode) are selectable via slow-control configuration bits. The base-line operational mode is peak detector. Peak detector captures the most positive point of the input signal so that the maximum of the shapers signals represents the pulse height conversion of the SiPM output signal. The digital triggers (64 trigger channels) are available on the 32 + 32 output pads of the two ASICs constituting the unit module based on 64 pixels. The analog outputs of the peak detectors are stored into 64 analog memories and read, at the occurrence of a trigger condition, by multiplexing the three-state output registers (LG and HG respectively) and then converted to digital counts by external ADC devices. An FPGA (Field Programmable Gate Array) could manage all the input/output operations from/to CITIROCs and SiPMs.

4. RADIOROC

Although the great results obtained by CITIROC (in the ASTRI-Horn system), it is not suitable for the detection of fluorescence light, where single photon counting with a double pulse resolution of few ns is needed. To do this, a new ASIC, named RADIOROC (RADIOgraphy Read Out Chip), is at the end of its design: it is an improvement of the CITIROC, with the possibility to have up to 100 MHz single photon counting, 64 channels and other features that will be described below.

Building a Monolithic Photo Detection Unit (MPDU) that can perform tasks perceived as requiring by applications is an attractive one. The MPDU is defined as the ensemble of SiPM (usually a matrix of sensors), signal processing FEE and a local intelligence (FPGA, or System on Chip, SoC FPGA). The progress in SiPM manufacturing, front-end ASIC and system integration associated with SoC design gives hope that this outcome can be achieved. An example of this kind of integration has been used successfully in the ASTRI-Horn Cherenkov telescope. Considering that product implementation of complex, low-power designs requires early integration of various hardware features with corresponding firmware onto device(s) it is important to define what kind of functionality and performance are required by users. The front-end signal processing is conceived to efficiently translate the SiPM analog signal into a digital one. Intuitively, the goal of the signal processing is to translate the electric pulses generated by photons in the SiPM in a series of measurable pulse amplitudes sampled by Analog-to-Digital Converter (ADC) into a numerical representation suited for further analysis. Ideally, this signal processing should yield a clean representation that is as close as possible to the user specifications. The case of space missions detecting fluorescence and Cherenkov light as well as atmospheric phenomena requires the detection of very faint and very intense light. To achieve both requirements, single-photon-counting as well as charge integration should coexist within an efficient MPDU. These modes must be selectable by the user by means of a set of programmable functions, implemented through a string of configuration bits, which instruct the front-end on the desired operating mode. In single-photon-counting mode, a double pulse resolution of a few ns ($\approx 10\ ns$) is enough to avoid pulses pile-up. Naturally, for the input stage, a programmable pole-zero cancellation technique is required to cope with long tail SiPM signals. Analog chains based on fast pulse sampling or pulse height measurement technique using peak detector should be implemented including pulse-shaping time and pre-amplifier gain programmability in order to cover the desired energy dynamic range (energy measurement from 1 pe up to several thousand pe within 1% linearity should be acceptable). ADC device integrated in the MPDU convert analog signals to digital data to be serially read-out. Digital triggers should be managed and selectable. Fast discriminators with user adjustable threshold by means of Digital-to-Analog Converters (DAC) provide the digital trigger signals that routed to a majority/topological trigger logic in the FPGA provide prompt MPDU trigger. Timing measurement should also be better than 100 ps RMS jitter. Masking of the digital triggers is also required to switch off potential noisy pixels. An adjustment of the SiPM high-voltage should be allowed using channel-by-channel DAC connected to the ASIC inputs. This allows for a fine SiPM gain adjustment at the system level to correct for the gain non-uniformity of SiPMs. Although current SiPMs have a much lower temperature dependence than a few years ago, temperature sensors embedded in the MPDU would be useful to compensate operating voltage for change in the gain of SiPM caused by local temperature variations.

CITIROC 1A is a good starting point in order to create the new RADIOROC applying some important modifications:

- the preamplifiers will be redesigned to let them work with a bigger bandwidth;
- a preamplifier will be added in the trigger chain;
- and a pole zero cancellation circuit will replace the

trigger fast shaper to have a trigger pulse at about 3 ns (unlike the previous configuration with about 18 ns).

A block scheme of the new chip, with all the modifications aforesaid, is shown in Fig. 4.

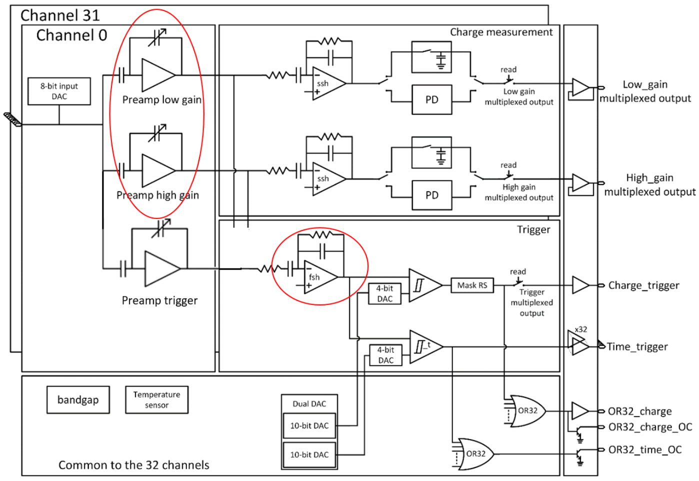


Figure 4: General block scheme of the CITIROC with the changes to be made for RADIOROC highlighted by red ovals.

5. Conclusions

In case of space missions, as well as for ground experiments, measurement of fluorescence, Cherenkov light or atmospheric phenomena require detection, with different time scale, of very faint and very intense light. Therefore, single photon counting and charge integration must coexist in the same front end to obtain optimum performance. The CITIROC 1A chip lends itself to the changes suggested in short time and the proposed integration of SiPM, FEE and FPGA in a MPDU drastically reduces power consumption and mass budgets, very important for any space mission and particularly for the proposed UHECR space missions as EUSO, POEMMA and similar ones. The progress in SiPM manufacturing, front-end ASIC and system integration associated with SoC design gives hope that this outcome can be achieved.

Summarizing, the main specifications of the new ASIC will be:

- SiPM high-voltage adjustment (with DACs connected to the ASIC inputs);
- double pulse resolution of a few ns ($< 10\ ns$) (to reduce pulses pile-up);
- programmable pole-zero cancellation trigger shaper (to cope with long tail SiPM signals);
- analog pulse height measurement using fast peak detector;
- wide energy dynamic range (energy measurement from 1 pe up to several thousand pe);
- 64 digital triggers;
- timing measurement better than 100 ps RMS;
- masking of the digital triggers (switch off potential noisy pixels);
- each parameter of the chip individually modifiable through slow control.

As can be seen from the simulations carried out on the ASIC design, shown in Fig. 5, 6, 7 and 8, the targets were achieved with regard to the pole-zero cancellation trigger response and the resulting double-pulse resolution of 10 ns (100 MHz).

Bode diagram looks like a bandpass filter with the high-cut frequeny being the actual bandwidth of the amplifier. The transfer function is shown in Fig. 5. The low-cut frequency is crucial to the recovery time of the preamplifier to be able to handle high pe rates for photon counting application.

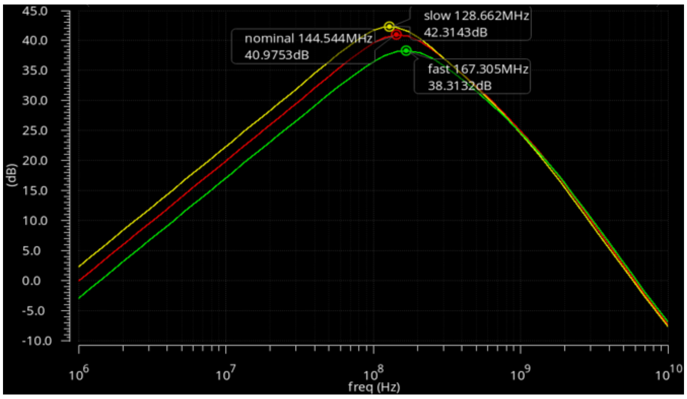


Figure 5: Trigger preamplifier Bode diagram for the 3 corner simulations.

The simulated SiPM signal input is shown in Fig. 6 and is related to one pixel of 6 x 6 mm^2.

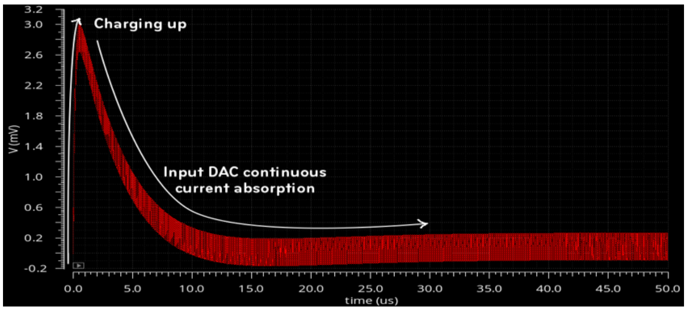


Figure 6: Input signal by triggering a photoelectron every 10 ns (100 MHz signal).

The preamplifier used for the trigger is a high-pass filter with the low-cut frequency chosen to optimize the recovery time of the preamplifier. The response of the preamplifier is shown in Fig. 7.

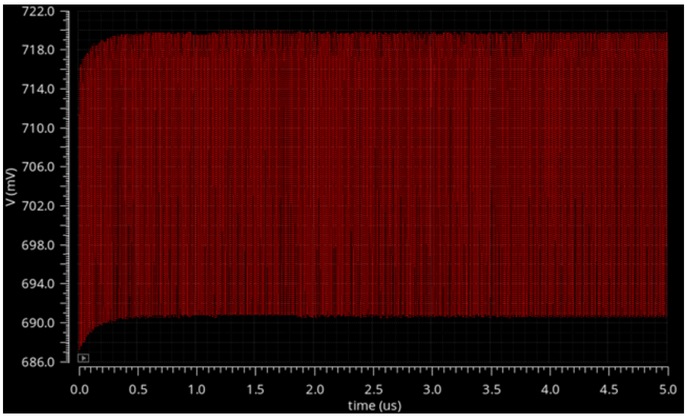


Figure 7: Preamplifier output with a 100 MHz input signal.

Resolving discriminator output for 100 MHz signal is shown in Fig. 8.

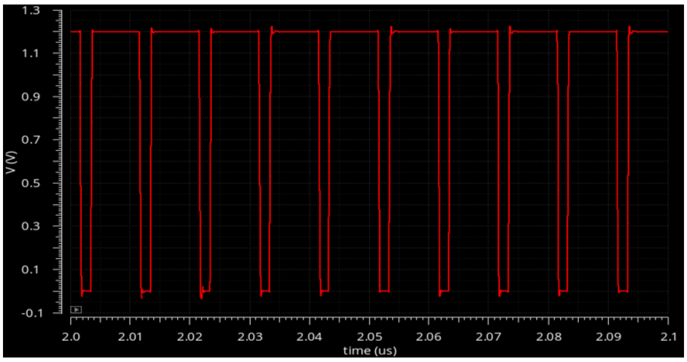


Figure 8: 10 ns discriminator output.

6. Acknowledgements

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