MUSIC: An 8 channel readout ASIC for SiPM arrays

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ABSTRACT

This paper presents an 8 channel ASIC for SiPM anode readout based on a novel low input impedance current conveyor (under patent[1]). This Multiple Use SiPM Integrated Circuit (MUSIC) has been designed to serve several purposes, including, for instance, the readout of SiPM arrays for some of the Cherenkov Telescope Array (CTA) cameras. The current division scheme at the very front end part of the circuit splits the input current into differently scaled copies which are connected to independent current mirrors. The circuit contains a tunable pole zero cancellation of the SiPM recovery time constant to deal with sensors from different manufacturers. Decay times up to 100 ns are supported covering most of the available SiPM devices in the market.

MUSIC offers three main features: (1) differential output of the sum of the individual input channels; (2) 8 individual single ended analog outputs and; (3) 8 individual binary outputs. The digital outputs encode the amount of collected charge in the duration of the digital signal using a time over threshold technique. For each individual channel, the user must select the analog or digital output. Each functionality, the signal sum and the 8 A/D outputs, include a selectable dual-gain configuration. Moreover, the signal sum implements dual-gain output providing a 15 bit dynamic range. Full die simulation results of the MUSIC designed using AMS 0.35 μm SiGe technology are presented: total die size of 9 mm^2, 500 MHz bandwidth for channel sum and 150 MHz bandwidth for A/D channels, low input impedance ($\approx 32\,\Omega$), single photon output pulse width at half maximum (FWHM) between 5 and 10 ns and with a power consumption of ≈ 30 mW/ch plus ≈ 200 mW for the 8 ch sum. Encapsulated prototype samples of the MUSIC are expected by March 2016.

Keywords: SiPM anode readout, photo-detection, current conveyor, pole zero cancellation, ASIC

1. INTRODUCTION

Gamma-ray stereoscopic observations can reconstruct with high accuracy the properties and direction of primary particles using several telescopes. Thus, identifying its gamma rays coming from sources.[2] Cascades of relativistic particles are generated when these high energy cosmic particles hit the atmosphere. These cascades emit faint flashes of Cherenkov light with nanosecond duration. Large telescopes focus the Cherenkov light onto fast photo-sensor arrays where the signal is read out.[3]

The Cherenkov Telescope Array (CTA)[4] is an international initiative to build the next generation observatory for ground-based gamma-ray astronomy. The CTA observatory will have several Imaging Atmospheric Cherenkov Telescopes (IACTs) of various sizes. The Large Size Telescopes (LSTs) cameras are equipped with photomultiplier tubes (PMTs) in order to convert the detected light into electrical signals that can be processed by specific readout electronics.

Silicon Photomultipliers (SiPMs) sensors became candidates to substitute PMTs in several research fields including gamma-ray astronomy.[5–7] These devices are characterized by extremely good timing response, moderate operating bias voltages (lower than 100 V), high gain (equal or larger than PMTs), low-amplitude after-pulses and high quantum efficiency. SiPMs also have the benefit of large flexibility in the creation of 2D arrays of sensors, robustness, compactness and insensitivity to magnetic field. On the contrary, these photo-detectors present higher capacitance and cross talk rates, although this technology is still evolving.

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This paper presents an 8 channel ASIC for SiPM anode readout based on a novel low input impedance current conveyor (under patent[1]). This Multiple Use SiPM Integrated Circuit (MUSIC) has been designed to serve several purposes, including, for instance, the readout of SiPM arrays for some of the Cherenkov Telescope Array (CTA) cameras. More specifically, it will enable the possibility to substitute multi-anode PMTs or PMT with large photo-cathode areas by SiPM arrays providing flexible readout.

The readout electronics proposed can be employed for the upgrade of the MAGIC cameras.[8] The 1-inch diameter PMTs used in MAGIC can be substitute for a self assembled matrix of 7 small SiPMs of 6 mm x 6 mm diameter size in order to cover the same pixel's detection area. The MUSIC ASIC performs an analog sum of the input currents of each pixel into one single output and thus it can be processed by the current PMT readout.

The MUSIC ASIC also includes digital and analog individual channel readout. This functionality could be employed in the Gamma Cherenkov Telescope (GCT) which is proposed to be part of the Small Size Telescopes (SSTs) of the CTA.[9] More specifically, this ASIC could be used instead of the discrete preamplifiers and the TARGET ASICs for readout in the Compact High Energy Camera for SiPMs (CHEC-S).[10] Other applications of this ASIC includes photon counting using the binary channels or star tracking utilizing an output current for an external integrator.

The paper is organized as follows. Section 2 details the main blocks of the architecture of MUSIC. The characteristics of the different operational modes of the chip are provided in section 3. The main aspects of the physical implementation of the ASIC are described in section 4. This paper concludes in section 5 providing some future avenues of research.

2. ARCHITECTURE

This section details the main aspects of the MUSIC chip architecture. Firstly, it includes an input stage based on a current preamplifier with multiple output currents to provide different functionalities. Secondly, a summation circuit is proposed to sum the signals read from different channels. Moreover, it contains a Pole Zero cancellation to cope with different time constants. Lastly, the different functionalities of the chip are here detailed.

2.1 Input current stage

A novel input stage based on a bipolar current mirror with double feedback loop is employed for SiPM anode readout (under patent[1]). The aim of this readout circuit is to provide a low input impedance in order to avoid affecting timing behavior of the SiPM and increase input current. The Low Frequency feedback loop (LF_{FB}) (based on[11]) controls the dc voltage (Va_{ref}) of the input node through the virtual short circuit of a folded cascode operational transconductance amplifier (OTA).[12] This OTA drives a follower closing the LF_{FB} loop. The High Frequency feedback path (HF_{FB}) employs a common-gate regulated cascode configuration[13] in order to keep the input impedance constant over the bandwidth of interest and thus the fast timing behavior of the SiPM is not affected. The design has been implemented taking into account that dominant pole should be set at the input node (SiPM parasitic capacitance is at the order of tenths of pF). In this way stability is not compromised when an important capacitance is added at the input.

The current division scheme here proposed splits the input current into differently scaled copies, which are connected to independent current mirrors to implement different features, as detailed in section 2.4. An schematic view of the input stage is illustrated in Figure 1 and the main characteristics of this block are detailed next.

- Low input impedance current conveyor: $\approx 32\,\Omega$ in the bandwith of interest.
- Anode connection for multi-channel photomultiplier common cathode arrays.
- Anode voltage control per channel by adjustment of the SiPM bias voltage. This voltage is configured using an internal DAC with 1V (9 bits) dynamic range. This adjustment may be used to change the gain or the photon detection efficiency of the photomultiplier, and therefore the gain of each channel.
- High bandwidth: larger than 500MHz.

- Low input referred noise for sensor capacitances between 10pF-10nF: (1) series noise lower than 2 nV/sqrt(Hz); (2) parallel noise lower than 20 pA/sqrt(Hz).
- Low power consumption: about 5mW.
- Individual SiPM pixel switch off by setting the anode voltage below breakdown (4V decrement in the SiPMs here employed). This allows to prevent full array failure in case of a defective pixel and to prevent excessive consumption in case of a high dark count rate or an excessive illumination on a pixel (e.g. moon observation in Cherenkov Telescopes).
- Power down mode for each individual channel.

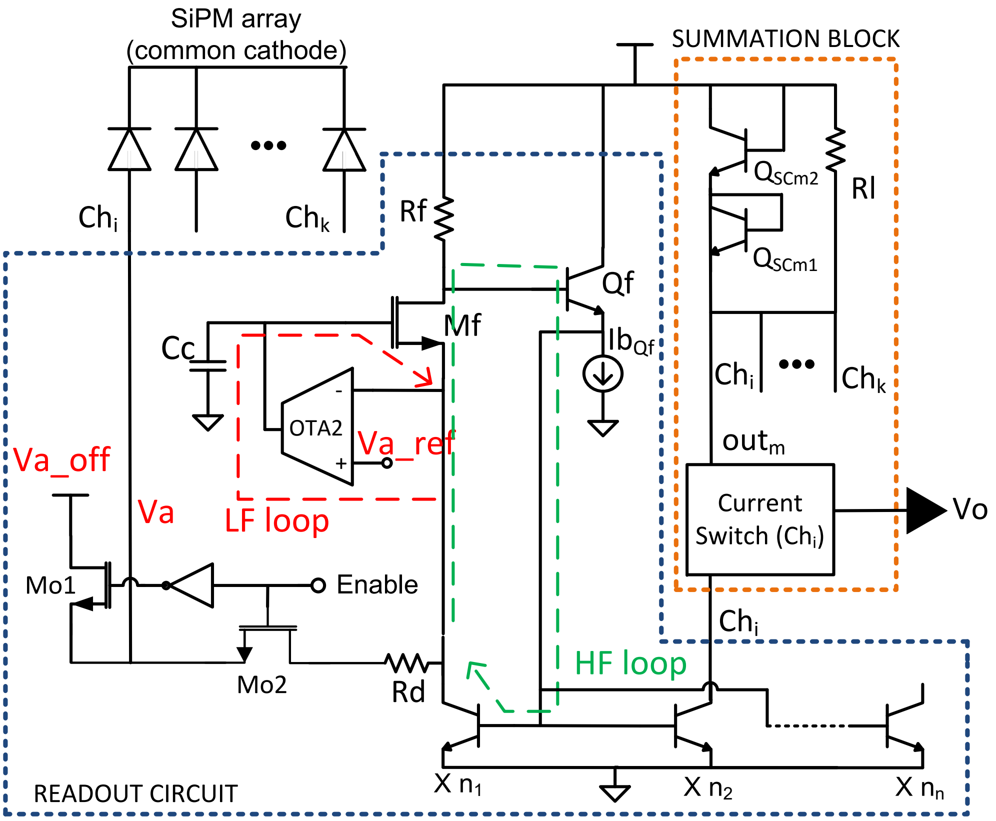


Figure 1: Input current stage including the readout circuit and the summation block.

2.2 Summation circuit

A summation circuit for summing one or more signals received from a photomultiplier array is also provided in the MUSIC ASIC (under patent[1]). The input signals can be added by simply connecting the outputs of the readout circuits previously described. However, if a single photo-diode is not functioning properly or gain non-uniformities exist between inputs, the result may be erroneous. To solve the problem, the channel summing module allows conditioned addition of one or more photomultiplier signals provided by the readout circuit.

In operation mode, each photoelectric pixel may be sensed by the corresponding readout circuit and then they may be summed at the current switch (CS), as detailed in Figure 1. The current switch implementation is shown in Figure 2. It acts as an active cascode for the input current mirror and it consists of two common base transistors $Q_{CBm,n}$ and an Operational Transconductance Amplifier (OTA2). The active cascode element sets the collector voltage of each mirror slave to the same collector voltage (Va) of the input transistor. This allows minimizing channel modulation errors (nonlinearity). The $Q_{CBm,n}$ transistor connected to the output of OTA2 works as a current buffer of the input current.

The summation element CS permits to disconnect one or more channels from the summing module. Note that each readout channel is coupled to a different current switch and then each output out_m of each CS is connected together to sum the different channels (analogously for output out_n). Each output of the summing element have a saturation control (transistors $Q_{SCm_{1,2}}$) and a different number of resistors (R_l) coupled in parallel to control the gain, as depicted in Figure 1. Finally, the different outputs from the CS can then be used to provide distinct gains and may be selectable to obtain different summation results.

The mathematical operation of the circuit may be described as:

$$Sum = S \cdot (k_1 \cdot ch_1 + k_i \cdot ch_i + \cdots + k_n \cdot ch_n) \tag{1}$$

The coefficients k_i may be controlled in the readout circuit by tuning the SiPM bias voltage and the coefficient S may be controlled at the summation element by selecting out_m or out_n as output. Hence, two different S gains can be configured.

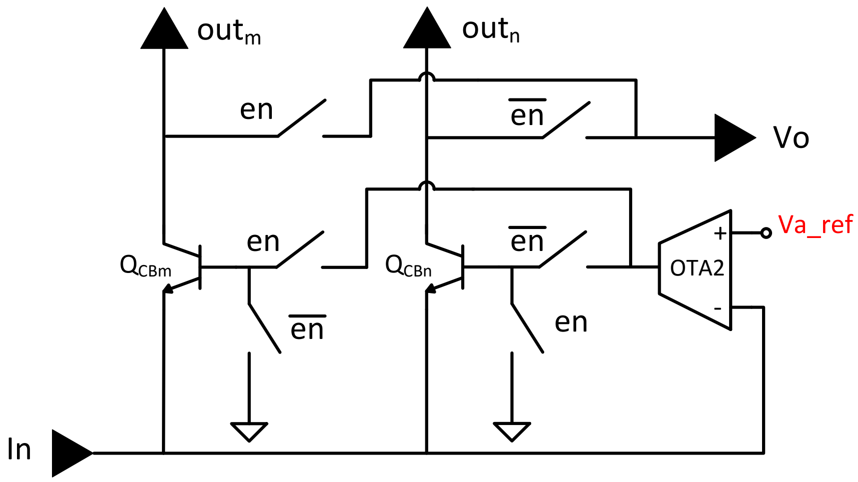


Figure 2: Implementation of the summing current switch.

2.3 Pole Zero Cancellation

The circuit contains a tunable Pole Zero cancellation (PZ) of the SiPM recovery time constant to deal with sensors from different manufacturers. Decay times up to 100 ns are supported covering most of the available SiPM devices in the market. The PZ reduces the peak duration of the signal and the tail produced by the sensor. The PZ cancellation can be used or bypassed in any operation mode.

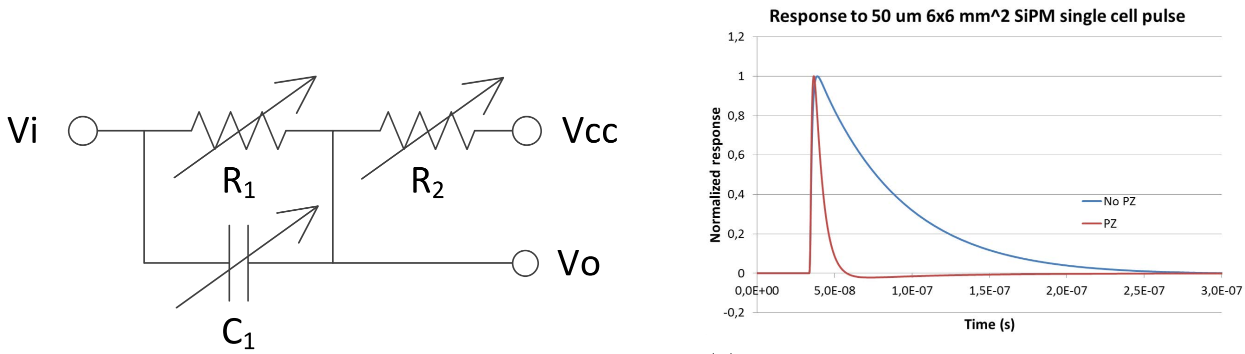
The equation that defines the behavior of the shaper can be obtained using the schematic view depicted in Figure 3a. The signal after the pole zero compensation for the time constant can be obtained by applying KCL at node V_o.

$$V_o = \left(\frac{R_2}{R_1 + R_2}\right) \frac{R_1 C_1 s + 1}{R_1 || R_2 C_1 s + 1} V_i \tag{2}$$

Thereby, the time constant can be computed as:

$$\tau = R_1 C_1 \tag{3}$$

The PZ shaper must be carefully tuned in order to: (1) cancel the time constant related to SiPM signal tailing edge; (2) compensate the undershoot/overshoot of the signal; (3) minimize the spill over (two events overlapped due to slow tails) by reducing the pulse width (full width at half maximum (FWHM) of the output signal lower than 10ns) and; (4) not jeopardize the signal peak due to excessive attenuation. For instance, increasing pull-up resistor (R2) will reduce current removed from input and thus decreasing signal attenuation. A good matching with the input time constant will provide a flat output. Figure 3b shows a typical signal before and after PZ compensation.



(a) PZ shaper circuit.

(b) Example of a typical signal of $\tau \approx$40ns with and without PZ cancellation.

Figure 3: Pole-zero compensation.

2.4 Common functions

MUSICR1 performs several functionalities using the different output currents from the readout circuit, as depicted in Figure 4.

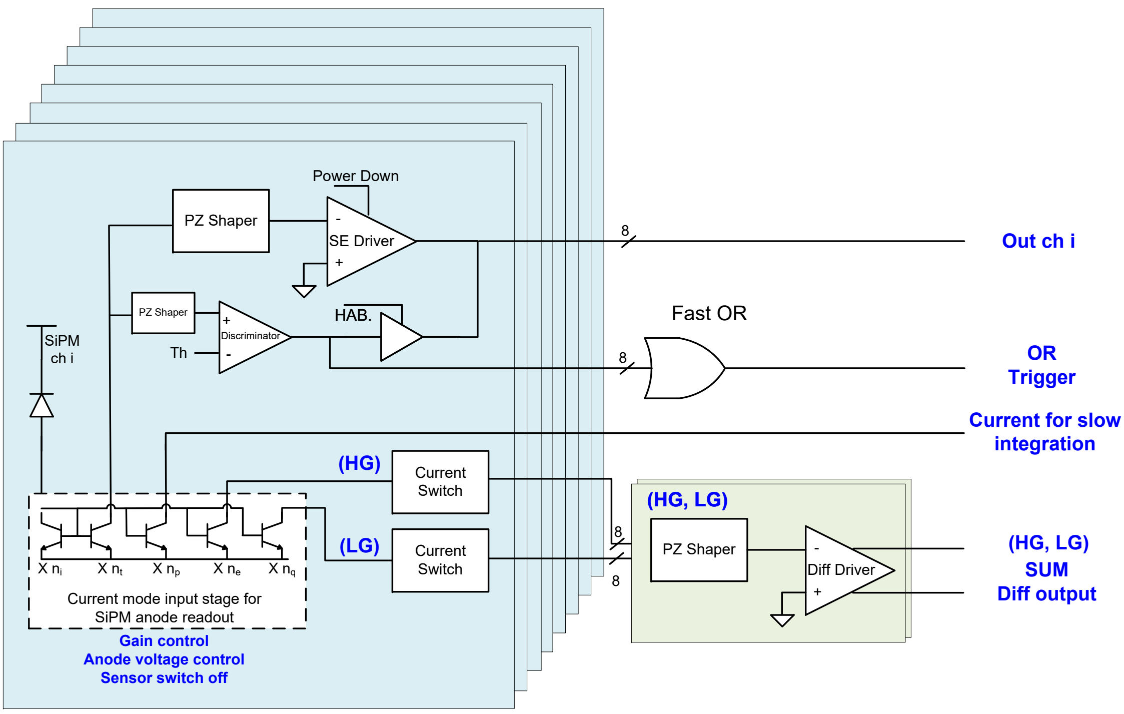


Figure 4: Functional block diagram.

The different operational modes are described next.

- **Channel sum:** The sum of the input signals is provided as a dual-gain output in differential mode using the high gain and the low gain currents from the readout circuit.
- **Analog channels:** 8 individual single ended analog outputs.
- **Digital channels:** 8 individual digital outputs are obtained using a discriminator.
- **Fast OR signal:** A trigger pulse is provided by performing an OR between any selection of digital signals.
- **Integrator current**: 8 output currents for an external slow integrator.

For each individual channel, the user must select the analog or digital output since both signals share the same output PAD. Moreover, a selectable dual-gain configuration is available for each functionality, the channel sum and the 8 A/D outputs. The PZ cancellation can be used or bypassed in any operation mode.

Other blocks are included to set the correct operation points of the circuit and configure several tunable parameters. For instance, individual SiPM pixel switch off is possible by reducing the over-voltage by 4V. It is important to highlight that every block and channel can be disabled (power down mode) with an specific control signal. Lastly, all these parameters can be reconfigured using an SPI (Serial Parallel interface) digital control.

3. FUNCTIONAL MODES CHARACTERISTICS

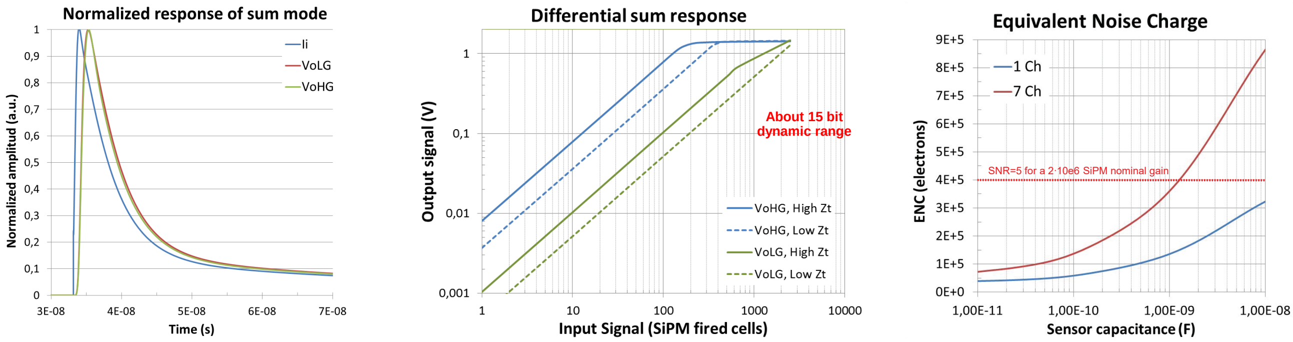
The MUSIC ASIC is designed to provide several functionalities. This section, describes the main characteristics of these operational modes.

3.1 Analog summation

An analog transistor circuit was developed to sum up, shape and amplify the SiPM signals of one pixel to a composite output without the drawback of summing the sensors capacitances. The MUSIC circuit provides two differential sum outputs with different gains, referred as High Gain (HG) and Low Gain (LG) channels. A differential voltage is provided at the output so noise can be filtered out by the common mode rejection of the data acquisition system in the measurements. Moreover, the sum block is configured with a double differential trans-impedance gain (Zt) and thus the sum of signals can be performed with 4 different gains. A summary of the main characteristics of the sum block is outlined next.

- The 8 channels contributing to the sum can be controlled individually.
- 15-bit dynamic range, as depicted in Figure 5b.
- Two configurable trans-impedance gains (Zt) at the sum block.
  - High Zt configuration: gain HG channel: 690Ω; gain LG channel: 90Ω.
  - Low Zt configuration: gain HG channel: 315Ω; gain LG channel: 45Ω.
- Configurable pole-zero cancellation providing output signals with a FWHM lower than 10ns. Possibility to bypass the PZ compensation.
- Power consumption of ≈ 200 mW for the 8 channel sum.
- Bandwith of 500MHz.

Figure 5a shows the response of the sum block to a fast SiPM pulse shape without using the PZ configuration. Noise has been evaluated in terms of Equivalent Noise Charge (ENC) which is computed as the RMS noise present at the output divided bv the charge impulse gain of the amplifier. The ENC of the HG channel varying the SiPM capacitances at the input signal line after 10ns integration is illustrated in Figure 5c. Observe from Figure 5a, that most of the charge of a fast SiPM pulse charge with 40 ns recovery time constant is at the first 10ns and thus the ENC mostly depends on this fraction of time. Figure 5c shows that the ENC increases with the input capacitance and the amount of active channels activated.



(a) Transient simulation of the normalized input and output response.

(b) Transient simulation of a single cell signal normalized to 12μA peak.

(c) Equivalent Noise Charge (ENC) for different sensor capacitances.

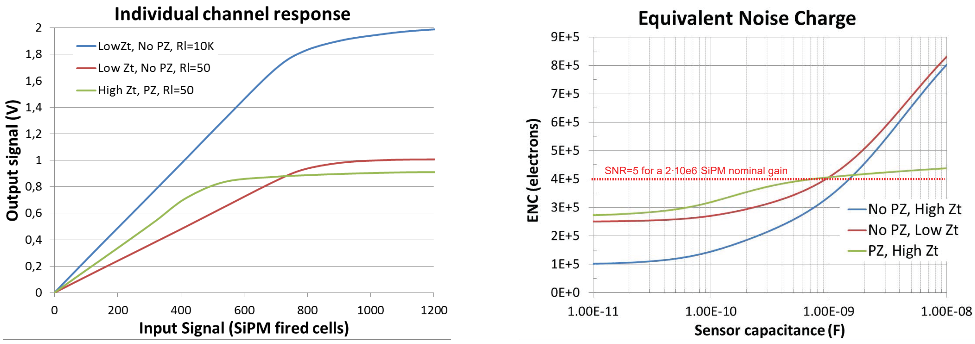
Figure 5: Summation block characteristics.

3.2 Analog output

The readout circuit also gives an amplified input current to provide individual analog single-ended (SE) outputs. The SE channels also shape and amplify the SiPM signals. The main aspects of the SE output signals are detailed next.

- The 8 analog outputs can be powered down using a dedicated slow control signal per channel.
- Two configurable trans-impedance gains (Zt) without PZ cancellation.
  - High Zt configuration: 480 Ω.
  - Low Zt configuration: 180 Ω.
- Dynamic range, as depicted in Figure 6a.
  - On high impedance loads: 2 V
  - On 50 Ω loads: 1 V
- Dynamic range compression, as depicted in Figure 6a.
  - Linear response for first half of the dynamic range.
  - Non-linear response for second half of it.
- Noise for low Zt.
  - On high impedance loads: lower than 600 μV rms
  - On 50 Ω loads: lower than 300 μV rms.
- Configurable pole-zero cancellation enabling output signals with a FWHM lower than 10ns. Possibility to bypass the PZ shaping.
- Power consumption is about 30mW per channel.
- Bandwidth above 150MHz.

A similar output pulse shape is expected for the analog channel compared to the sum block with the only difference that here the signal is single-ended. Figure 6b shows that the ENC after 10ns integration augments with the detector capacitance. Observe from Figure 6b the impact of the PZ cancellation on the ENC; SNR is slightly degraded for small sensor capacitances (signal attenuation); on the contrary, SNR is improved for high capacitance limited, in this case, by the low frequency (LF) noise. Note that the PZ circuit actuates as a pass-band filter attenuating the LF region and thus for fast integration times the SNR (ENC) is improved.



(a) Transient simulation of a single cell signal normalized to 8μA peak.

(b) Equivalent Noise Charge (ENC) for different sensor capacitances.

Figure 6: Analog single channel characteristics.

3.3 Digital output

Individual digital outputs are obtained using the preamplifier readout, a shaper and a comparator. Each channel delivers a binary signal encoding the amount of collected charge in the duration of the digital signal using a time over threshold technique (TOT). These binary outputs are obtained using a discriminator with a programmable threshold. The advantage of TOT readout is that minimizes additional components (no ADC required) since digitization can be performed by Time to Digital Converters (TDCs) on FPGA.[14] The main performance aspects of the digital channels are outline next.

- The 8 digital outputs can be powered down using a dedicated slow control signal per channel.
- Low jitter for more than 5 cell signals: lower than 5ps.
- Configurable pole-zero compensation before comparator enabling output signals with a FWHM lower than 10ns. Possibility to bypass the PZ cancellation.
- Static power consumption is negligible.

Figure 7 illustrates the time over threshold response of the digital output for different SiPM fired pixels. Despite the ToT application of the binary output, the fast shaping applied to pulse shape also allows the possibility of photon counting.

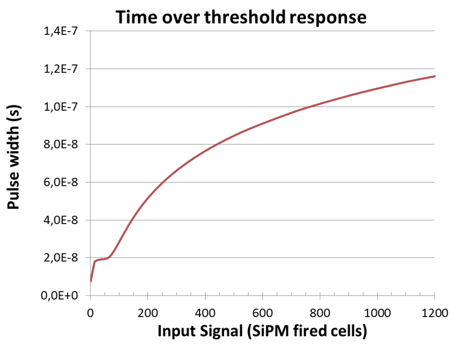


Figure 7: Time over threshold response for different input fired signals.

3.4 Other output features

Two additional features are included in the MUSIC ASIC to provide other functionalities. A current for an external slow integrator is also provided for each readout circuit (8 channels). In this version of the chip, the integration is done outside the ASIC by using an operational amplifier, a resistance and a large capacitance. Future versions of MUSIC are expected to include all this functionality inside the die. This low frequency signal is intended for current monitoring and star tracking (per channel or sum). Moreover, the fast comparator enables the possibility to use any of the digital channels as a trigger. Thereby, a logic OR of all discriminated channels deliver a common time signal to be used as a trigger.

4. MUSIC PHYSICAL IMPLEMENTATION

The MUSICR1 has been developed by using the AMS 0.35 μm SiGe BiCMOS technology. Thus, it can be operated in the -40°C to +125°C junction temperature range. A total die size of 9mm2 (3274μm x 2748μm) has been required to include the described functionality. MUSICR1 is formed by several blocks: (1) input stage; (2) 8 SE analog/digital channels and (3) a sum block. These blocks employ a common biasing generation structure. All blocks and bias references are controlled by the same common logic (slow control). Some of the signals are common to different blocks (for instance, the PZ configuration) while others are in separated registers (such as the enabling switches).

Different power domains are present in the design. The different ground connections used in the circuit are separated logically during design but are all connected to the same substrate. For the power supply, different power rails are used inside the ASIC until the PCB level (there they could be joined to the same power supply). This permits of external filtering if needed, avoiding any noise transmission between power supplies. Several redundant power pads have been placed in the design to reduce the parasitic inductance and voltage drop.

Encapsulated prototype samples using a 64-QFN 9x9 mm package are expected by March 2016. A summary of the main characteristics of the circuit are detailed in Table 1.

Table 1: Main characteristics of the MUSIC circuit.

List of specifications
500MHz bandwidth for channel sum.
150MHz bandwidth for A/D channels.
Low input impedance (≈32Ω).
Single photon output pulse width at half maximum (FWHM) between 5 and 10ns.
Power consumption of ≈30mW per individual channel.
Power consumption of ≈200mW for the 8 channel sum.
Adjustable input node DC voltage per channel.
High dynamic range (15bit) to operate SiPM at high over-voltage.
Zero components interface between sensor and device.
Total die size of 9mm^2 (3274μm x 2748μm).
64-QFN 9x9mm package.

5. CONCLUSIONS

An 8 channel ASIC for SiPM anode readout in CTA cameras is proposed. MUSIC includes three main operational modes: (1) SiPM pixel summing in differential mode; (2) 8 individual single ended analog channels and; (3) 8 individual digital outputs. Additionally, a trigger pulse is provided by performing an OR between the binary signals and an output current for an external integrator is also available. The MUSIC is designed for high speed sampling: pulse width between 5 and 10 ns. Future work includes a technology migration to a lower node, to provide lower noise and reduced the power consumption. Moreover, higher voltage range to decrease SiPM bias voltage up to 10 V and an internal integrator with a low time constant of 10 to 100 ms are planned for future versions of the ASIC. Lastly, prototype samples of the MUSIC are expected by March 2016.

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