Gain characterisation of RF ampliers for silicon photomultiplier scintillation detector

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1 Introduction

A proposed silicon photomultiplier - scintillator detector uses the electron-positron annihilation 511 keV photons emitted after the decay of the short lived radioisotope ^{26}Al to infer the number of 15-30 MeV gamma rays emitted in a laser-plasma interaction. ^{26}Al is produced when photons of such energy are incident on pure ^{27}Al, and can be identified by the characteristic 6.35 s half-life of the decaying β^+ emissions [1]. Hence, the capability of the detector to resolve the 511 keV photopeak is essential.

The peak heights of 511 keV scintillation events in a bismuth germanate (BGO) crystal produced by a silicon photomultiplier (SiPM) detector are typically in the region of tens of millivolts*, which is below the lower threshold of common multi-channel analysers (MCAs) which might be used to easily digitize such signals. An MCA characterised by the author has demonstrated a typical range of 260 mV - 3.5 V for peak height digitization, for input pulses of 400 ns, which are representative of BGO scintillation pulses [2]. This indicates that an amplifier with a gain factor of around 25 is required, assuming pulse widths are unaffected by the amplifier. Larger pulse widths enable easier digitization of lower amplitude pulses, so amplifiers which also elongate pulses may be viable with lower gains. To exploit the full dynamic range of SiPMs, a useful amplifier should not saturate below 1V input amplitude. However, for single X-ray event detection, maximum voltages of 100 mV are typical.

in this report, the gain and saturation limits of three charge sensitive preamplifiers (CSPs) designed for use with radiation detectors are characterised with pulse signals from a 36 mm^2 active area KETEK SiPM, using 400 ns LED pulses at $\lambda = 520$ nm to simulate scintillation light from BGO†. The performance of these is compared with a KETEK preamplier designed for use with SiPMs characterised using directly input 400 ns square pulses of varied amplitude.

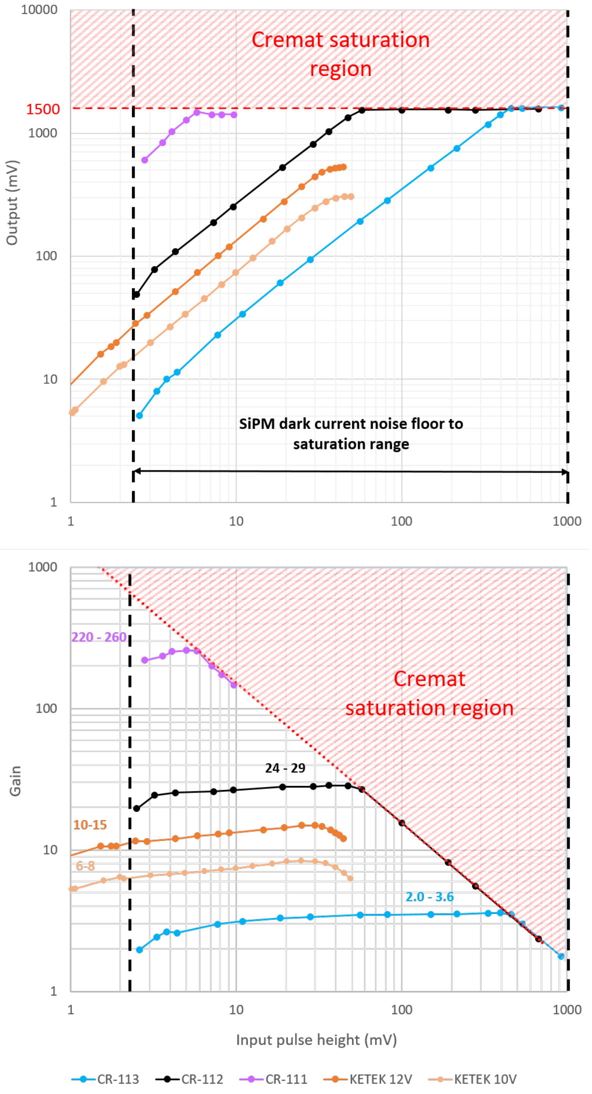

Figure 1: Output (top) and gain (bottom) vs. input pulse voltage for three CSPs, CR-111, CR-112 and CR-113, all driven at 13.6 V, and the KETEK SiPM preamplifier at 10 and 12 V operating voltages.

2 Preamplifier gain behaviour

Fig. 1 (bottom plot) demonstrates that the three CSPs tested (CR-111, -112 and -113) have successive order of

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[*] up to around 100 mV for a small (1 cm cube) BGO crystal

[†] BGO peaks at $\lambda = 480$ nm and has a primary decay time of 300 ns

magnitude reductions in gain in their linear region, and all saturate consistently with 1500 mV maximum output voltage, shown by the red dotted line in the upper plot in the figure. The KETEK SiPM preamplifier has gain of 6-8 and 10-15 when operated at 10 V and 12 V driving voltage, respectively, with a relatively low saturation limit when compared with the CR-113 and -112 amplifiers. This prevents reliable resolution of SiPM signals in excess of just 50mV, which is just 5% of the the typical dynamic range of a single chip SiPM. CR-113, the low-gain CSP, offers the largest linear region, saturating with SiPM pulses of ≈ 0.45 V, which would allow the resolution of scintillation events by X-rays up to $\approx$ 5 MeV. Normalised example traces in Fig. 2 show that the CSPs increase the widths of pulses to μs, in addition to increasing amplitudes, which has been found to lower the threshold of detection of the MCA due to easier digitization. This ensures that even with the low gain of the CR-113 with small input pulses, the MCA should be capable of resolving scintillation pulses corresponding to X-ray energies as small as 200 keV. In contrast, all the other amplifiers appear to be driven into saturation by 90 mV SiPM pulses of 511 keV X-rays. As previously mentioned, it should be noted that larger crystals (which are preferable in such a detector as they increase the number of 511 keV photons detected, making the characteristic decay easier to identify) result in fewer optical photons detected by the SiPM due to an increase in the average number of internal reflections required for a photon to reach the SiPM. As a result, a 511keV scintillation event will produce smaller amplitude SiPM pulses, which have been observed to fall below the saturation limit of the higher gain CR-112 CSP.

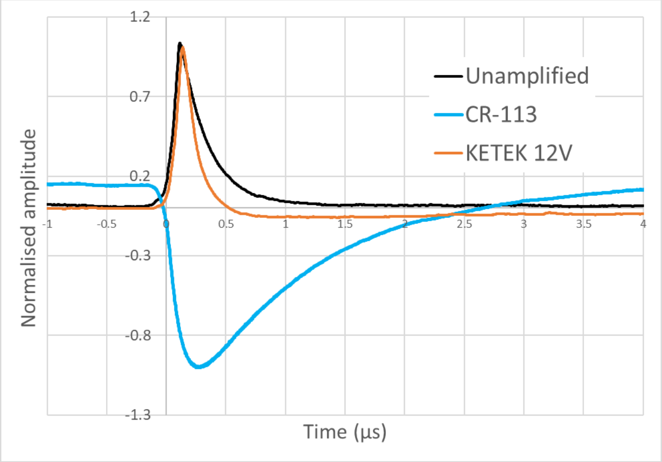

Figure 2: Example SiPM traces with 400 ns LED pulses, shown amplified with the KETEK preamplifier, the low-gain CR-113 CSP, and unamplified. As well as inverting and amplifying the amplitude of pulses, the CSP also significantly increases the pulse width to $\approx 1\mu s$. The higher gain CR-112 behaves similarly.

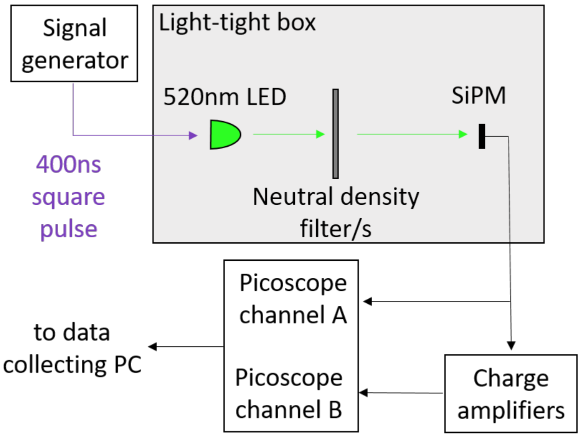

Figure 3: Set-up diagram illustrating simulated scintillator pulse and subsequent SiPM signal passing through set-up for gain characterisation of CSPs.

SiPMs produce traces like those shown in the black trace in Fig. 2 when a 400 ns pulse is incident, with a sharp rising edge as incident photons cause avalanche breakdown and fast rising macroscopic current flow, and then an exponential decay as the current is quenched and the bias voltage restored. Typical non-shaping amplifiers preserve this shape, simply changing the amplitude of such pulses, which is how the KETEK amplifier tends to behave. However, CSPs like the CR-113 act as integrating amplifiers, and elongate input pulses as well as producing an inverted polarity amplified output. Amplifiers which increase pulse durations have the drawback of reducing ability to temporally resolve consecutive events, but has the benefit of making for easier signal digitization to form pulse height spectra. A pulse pile-up algorithm could also be applied to traces to improve the temporal resolution of systems using CSPs if necessary [3].

Fig. 1 illustrates, particularly in the lower plot of the amplifiers' gain, a clear trade-off between the dynamic range of the CSPs and their gain. The low-gain CR-113 amplifier has the highest saturation limit at signal amplitudes of $\approx$ 500 mV, while the $\approx$ 90 mV 511 keV pulses would drive the other amplifiers into saturation.

3 Method

As shown by the set up in Fig. 3, the CSPs were characterised by pulsing a 520 nm LED at 400 ns on a 2x2 array 36 mm^2 SiPM biased at 30 V, and monitoring the output before and after amplification using a 50 Ω coupled Picoscope 6404D oscilloscope, with data collected via the complementary Picoscope6 software. Neutral density filters were used to incrementally change the intensity of light incident on the SiPM, hence varying the amplitude of pulses input to the CSPs. The KETEK amplifier and the two additional amplifiers discussed in §5 were instead directly input with 400 ns square pulses using a variable amplitude signal generator, and the peak heights similarly recorded using a 50 Ω coupled oscilloscope. §5 has more details regarding set-up and method used to characterise the KETEK amplifier.

4 Conclusions

The high gain and pulse lengthening properties of the CR-112 amplifier make it ideal for use with the small signals from SiPM coupled BGO crystals and the characterised MCA for resolution of 511 keV scintillation events from beta decay of gamma activated ^{27}Al. It's low saturation limit may become an issue for smaller crystals, as a 36 mm^2 SiPM will have better light collection efficiency, leading to larger electrical pulse outputs. This can be overcome by using the lower gain CR-113 amplifier, or by reducing the bias voltage applied to the SiPM. Future work will investigate the performance of detectors with varied scintillator crystal sizes, coupled with the different amplifiers used here, and their energy range and resolution determined using a ^{22}Na radioactive calibration source.

References

[1] R. J. Clarke et al. , 2006 *Detection of short lived radioisotopes as a fast diagnostic for intense laser-solid interactions*Appl. Phys. Lett. **89**, 141117 (2006)

[2] J. K. Patel, C. D. Armstrong and D. Neely, 2019 *Performance of a Kromek multi channel analyser for a silicon photomultiplier - scintillator gamma ray detector* CLF, STFC, Rutherford Appleton Laboratory.

[3] A. Dasgupta, 2019 *Detection and spectral analysis of X-ray radiation from laser plasma interactions.* University of Bristol.

5 Appendix

Additional characterised amplifiers

The KETEK SiPM preamplifier and two additional amplifiers were characterised using signal generated square input pulses with variable amplitude, and RF attenuators to produce amplitudes below the lower limit of the signal generator used. The additional low power amplifiers exhibited the same low saturation limit issues as the KETEK, so were not seen as fit to be included in the main body of this article for in the interest of clarity, but details of their results are appended for completeness.

The additional devices were unbranded, low-cost RF amplifiers designed for use with radio electronics, with bandwidths of 85-100MHz and 0.1-2000 MHz, henceforth referred to as 100 MHz and 2 GHz amplifiers, respectively. Their gain behaviour is shown at 10 V and 12 V, in Fig. 5 alongside the KETEK amplifier for comparison.

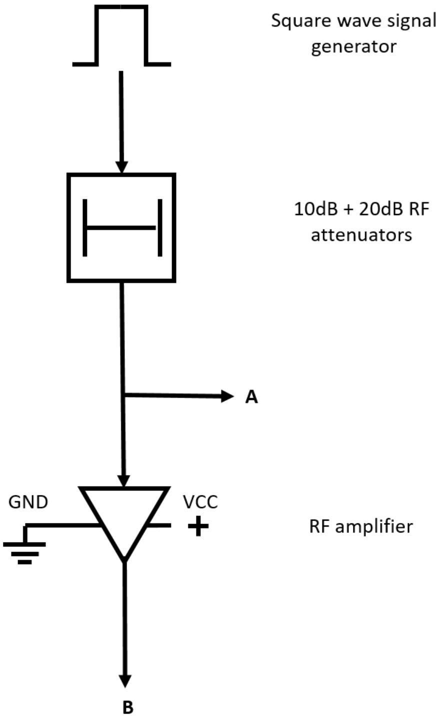

Figure 4: Block diagram of set up used for characterisation of RF low power amplifiers. Labels 'A' and 'B' denote the oscilloscope channels to which the signal is output at the illustrated points in the set up. 'A' is the amplifier input signal, and 'B' is the amplifier output signal. The RF amplifier in the diagram represents where each of the three amplifiers were connected.

The highest gain amplifier of the three (100MHz) then characterised at reduced voltages so that an operating regime of useful gain with increased saturation limit might be identified, and the results are shown. Even at the lowest operating voltage (6 V) the amplifier was functional at, it saturated at amplitudes significantly below the expected 90 mV signals from 511 keV BGO events as detected by a typical SiPM.

Hardware list

- SRS DG645 Digital Delay Generator - `https://www.thinksrs.com/downloads/pdfs/catalog/DG645c.pdf`
- TENMA programmable bench DC power supply. Part no.: 72-2535. Datasheet - `http://www.farnell.com/datasheets/2724049.pdf?_ga=2.230339036.1795680448.1566202840-662613774.1566202840`
- PicoScope 6000 Series model: 6404D. Datasheet - `https://www.picotech.com/download/datasheets/PicoScope6000CDSeriesDataSheet.pdf`

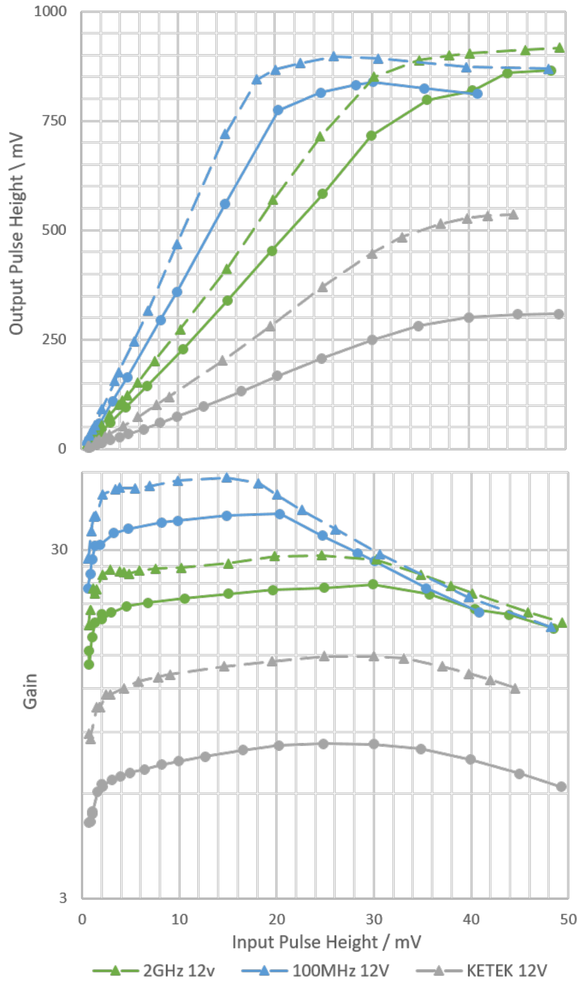

Figure 5: Output (top) and gain (bottom) vs. input pulse voltage for each of three low power amplifiers, driven at 10 V (solid lines) and 12 V (dashed lines).

- Amplifiers to be characterised:
    1. Cremat CR-113 charge sensitive preamplifier - https://www.cremat.com/CR-113-R2.1.pdf
    2. Cremat CR-112 charge sensitive preamplifier - https://www.cremat.com/CR-112-R2.1.pdf
    3. Cremat CR-111 charge sensitive preamplifier - https://www.cremat.com/CR-111-R2.1.pdf
    4. KETEK 0.1-1000 MHz pre-amplifier for SiPM (henceforth, KETEK amp.). Shown below with cover fastened and with cover removed to expose circuitry. SiPM Evaluation Kit Product Brochure (for KETEK amplifier) - https://www.ketek.net/wp-content/uploads/2016/01/KETEK-SiPM-Evaluation-Kit.pdf
    5. 85-100 MHz RF amplifier, unbranded (henceforth, 100 MHz amp.). Seller description and specifications- https://www.ebay.co.uk/itm/NEW-1PC-FM-High-frequency-FM-100MHz-RF-\\Amplifier-Transmitter-Amplifier-1W/173807165395?hash=item2877b6dfd3:g:LJYAAOSwv1db1nHe
    6. 0.1-2000 MHz RF amplifier, unbranded (henceforth, 2 GHz amp.). Seller description and specifications - https://vi.vipr.ebaydesc.com/ws/eBayISAPI.dll?ViewItemDescV4&item=382904261120&t=0&tid=310&category=163853&seller=motorcyclesaler&excSoj=1&excTrk=1&lsite=3&ittenable=false&domain=ebay.co.uk&descgauge=1&cspheader=1&oneClk=1&secureDesc=1#

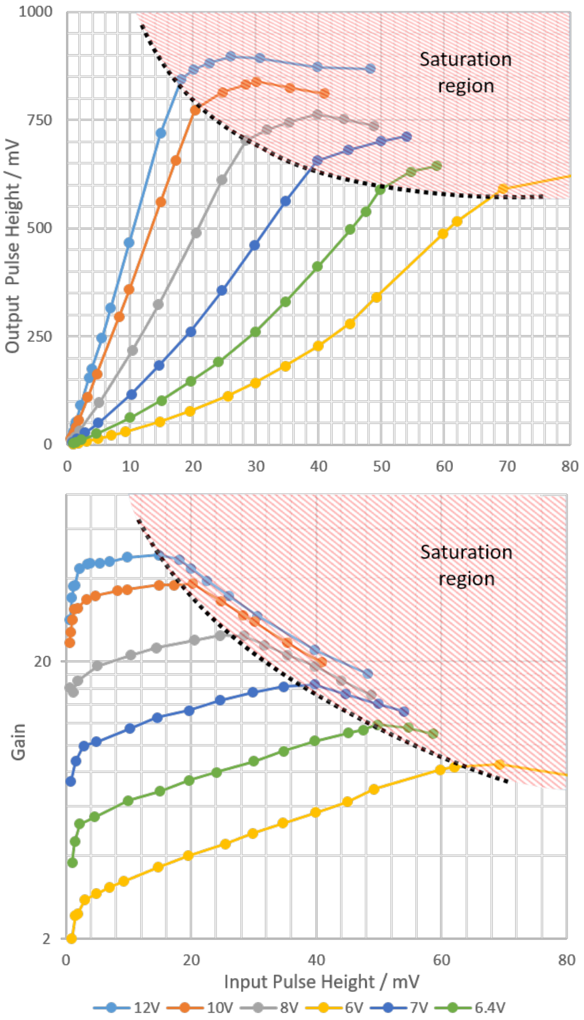

Figure 6: Output (top) and gain (bottom) vs. input pulse voltage for the 100 MHz amplifier, operated at six different voltages. The black, dotted lines indicate the saturation limit, and the red shaded area illustrates the saturation region.

- 520 nm LED

- DDS Signal Generator/Counter with variable amplitude (unbranded).
- Telegartner 50 Ω RF BNC attenuators:
    - 20 dB. Part No.: J01006A0837. Datasheet - `https://docs-emea.rs-online.com/webdocs/1420/0900766b81420994.pdf`
    - 10 dB. Part No.: J01006A0836. Datasheet - `https://docs-emea.rs-online.com/webdocs/1420/0900766b81420995.pdf`

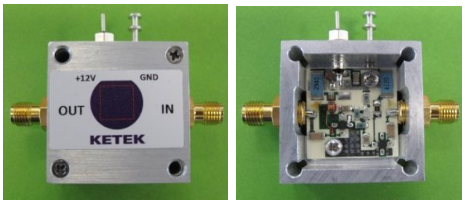

Figure 7: KETEK 0.1-1000 MHz pre-amplifier for SiPM

Figure 8: 85-100 MHz RF amplifier

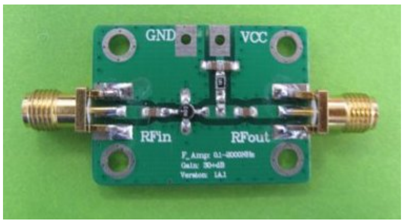

Figure 9: 0.1-2000 MHz RF amplifier