# A Survey of Power Supply Techniques for Silicon Photo-Multiplier Biasing

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**Abstract**— In the past few years Silicon Photo-multiplier (SiPM) has emerged as a new detector in various applications due to its promising characteristics for low light detection. However SiPM has certain limitations out of which temperature dependence of gain is an important parameter which limits the application fields to temperature controlled or indoor environment. Change in temperature changes the breakdown voltage and hence the gain; therefore the biasing voltage needs to be trimmed according to temperature for maintaining the constant gain. This paper explores different power supply techniques that have been used for SiPM. Many commercial power supplies are compared and different approaches which are tried by various research groups for maintaining stable gain are discussed.

**Keywords**— Silicon Photomultiplier, SiPM, Power Supply, Temperature Compensation, Bias Correction of SiPM, Gain stabilization, Automatic Gain Correction.

## I. INTRODUCTION

Avalanche Photo-diodes (APDs) are widely used in photon detection since very long time. In past few years, Silicon Photo-Multiplier (SiPM) has emerged as a new detector in applications where very low density photon detection is required such as high energy physics experiments, medical imaging, etc. The promising characteristics and performance of SiPM has proved it as a solid state alternative to the traditional Photo Multiplier Tube (PMT). SiPM offers features such as compact size, single photon resolution, high gain (~$10^6$), fast response (~100 ps), high photon detection efficiency (~60%), insensitivity to magnetic fields and relatively small operating voltage (~100V) when compared with PMT [1-3]. SiPM also has certain limitations such as dark counts (~0.1 MHz/mm$^2$), optical cross-talk, and after-pulsing along with high temperature dependence of gain (3% - 10% /˚C) as compared to PMT. These limitations are being rapidly improved with newer versions of SiPM. However, for a strong signal pulse with high number of photons, the functionality of device is not affected much by high dark counts [4].

The gain of the SiPM is a function of applied electric field for biasing of SiPM; which in turn will be dependent on the operating conditions such as biasing voltage, operating temperature, etc. The precise control and stability of biasing voltage is necessary for adjusting desired gain. Also SiPM has a temperature coefficient for the breakdown voltage. A typical temperature coefficient of breakdown voltage for Hamamatsu SiPM is of 50 mV/˚C [5].

For a fixed biasing voltage of SiPM when temperature rises, the gain will decrease due to the positive temperature coefficient of breakdown voltage. For a typical overvoltage, small change in SiPM temperature causes the gain to vary by several percent at a fixed biasing voltage condition. In conclusion, the temperature effects on SiPM along with precise control of biasing voltage are important parameters for proper operation of SiPM in stable gain mode.

Different power supply techniques and approaches are discussed in this paper and it is organized as follows: Section II discusses commercially available power supplies that can be used with SiPM. Section III shows some custom power supplies made for SiPM operation, testing and characterization purpose. Section IV represents different approaches taken by various research groups for achieving stable gain mode operation of SiPM in varying operating conditions. Section V concludes the paper and discusses best possible approach for SiPM power supply implementation.

## II. COMMERCIALLY AVAILABLE OPTIONS FOR SIPM

Out of the many commercially available power supplies, Keithley's Model 6487 [6] is a one of the best option, being widely used for biasing SiPM . It is single channel voltage source with built-in pico-ammeter. The output voltage can be set from 0.2 mV to 505V with the step sizes of 0.2 mV in 10V range, 1 mV in 50 V range and 10 mV in 505 V range. The maximum ripple voltages in these ranges are: 50 $\mu V_{p-p}$ in 10 V range, 150 $\mu V_{p-p}$ in 50 V range and 1.5 $mV_{p-p}$ in 505 V range. The pico-ammeter is capable of measuring the minimum current of 0.01 pA to maximum current of 20 mA in different ranges. It has automated voltage sweeps for I-V characterization which makes it ideal for testing of SiPM. Also the interfacing options (IEEE-488 and RS-232) make it easier for use of this power supply in automated test and measurement systems like LabVIEW.

Agilent Technologies has a power supply (Model 6614C) [7] which is similar to Keithley's Model 6487, but with lower precision specifications. The single channel output voltage can be set from 0V to 100 V with maximum current capacity of 0.5 mA. The programming step size for output voltage is 25 mV with maximum ripple voltage of 5 mVp-p. It also has a current meter which can measure current with accuracy of 2.5 μA, along with interfacing options of IEEE-488 and RS-232. Tektronix Model PWS4721 [8] is also capable of supplying output voltages between 0V to 72 V with maximum current capacity of 1.2 A. It has maximum output ripple voltage of 3 mVp-p. The output voltages can be set with step size of 1 mV. Typically, commercially available power supplies which are capable of giving the output voltages greater than 60 V, have specifications less precise than [6]; since they are used in general purpose applications which does not require very precise control of output voltage.

## III. CUSTOM POWER SUPPLIES MADE FOR SIPM OPERATION AND TESTING

CAEN has a complete SiPM development kit [9] which can be used for testing and characterization of SiPM along with provision of data logging as shown in Fig. 1. The parameters of SiPM under test such as gain, photon number resolving power and dark count rate at different photo-electron threshold etc. can be found with help of this kit.

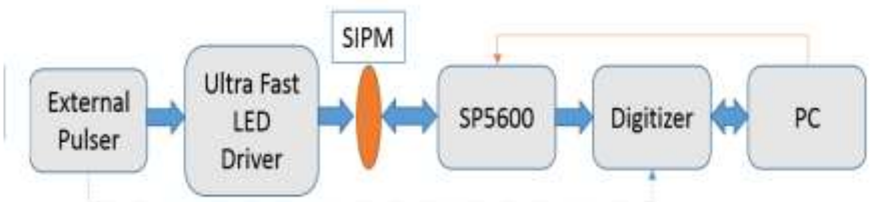


Fig. 1 Block diagram of CAEN Silicon Photo-multiplier development kit

The module SP5600 used in development kit in [7] is a 2-channel Power Supply and Amplification Unit (PSAU) [10] which can mount two SiPMs. The PSAU supplies the bias voltage for SiPMs and also incorporates a feedback circuit that will stabilize the gain of SiPM against temperature variations. The PSAU also has an amplifier with variable gain up to 50 dB, one leading edge discriminator per channel and a coincidence circuit for event trigger logic with provision of USB for parameter configuration via software. Fig. 2 shows the block diagram for SP5600 PSAU. The PSAU is capable of providing biasing voltage up to 120V with the resolution of 1.8 mV and temperature feedback with resolution of 0.1 ˚C. This unit is meant for indoor environment use only.

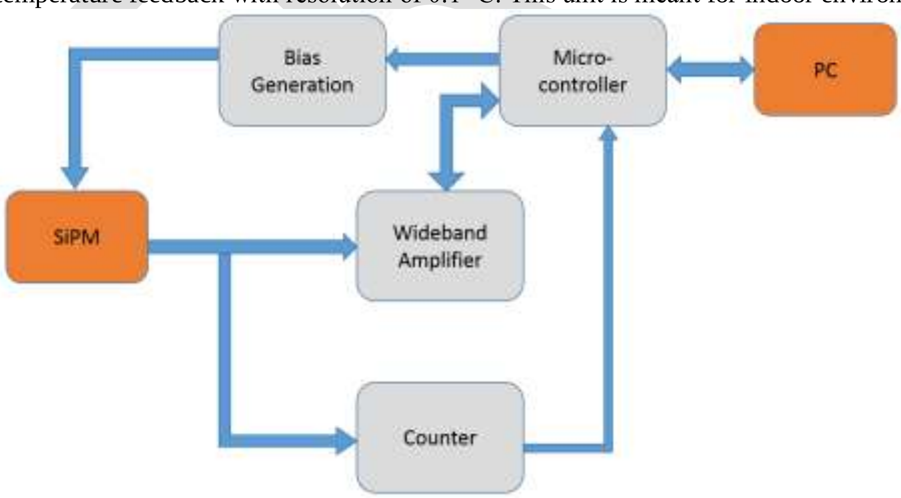


Fig. 2 Block Diagram of CAEN 5600 Power Supply and Amplification Unit (PSAU)

The AiT instruments also has complete SiPM testing and data logging system which uses a SiPM base for SiPM mounting, a SiPMIM16 interface module [11] and MDU20-GI16 integrator and interface control module [12]. This setup uses AiT instrument's HV80 as a power supply for SiPM [13]. The HV80 can supply 10V to 80V adjustable output voltage which can be controlled by 0 to 2.5V control voltage. HV80 can supply 4mA output current with adjustable overcurrent shutdown, output voltage and current monitoring features. But this unit is also meant to be used in indoor, temperature controlled environment only.

Other than the CAEN and AiT instruments SiPM power supplies, there are some custom power supplies that are meant to be used with particular SiPM only. The Excelitas' Lynx SiPM module Lynx-A-33-050-T1-A [14] uses Excelitas C30742 series SiPM and it consists of stable power supply for SiPM operation, thermoelectric cooler for temperature control and a low noise amplifier. This unit takes +5V as supply voltage and gives directly the output pulse after amplifier in range of 0-5V.

Another example is the SensL MicroM-EVB and MicroB-EVB boards which are to be used with SensL L-series, M-series and B-series SiPM. These boards have inbuilt power supply for biasing the SiPM and a pre-amplifier for amplification of SiPM output pulse. The power supply module in MicroM-EVB board gives a fixed output voltage of 29.5V and in MicroB-EVB board gives a output voltage of 27V for corresponding series SiPM.

## IV. OTHER APPROACHES FOR SIPM BIASING

In previous sections, all power supplies and techniques used for biasing of SiPM are commercially available and majority of them are meant to be used in temperature controlled environment since SiPM gain has significant temperature dependence (3% - 10% /˚C). These variations in gain are critical when operated with large gain of SiPM (~$10^6$). For stabilizing the gain of SiPM against temperature variations, the temperature can either be kept constant or controlled while operating in closed environment. But, when SiPM is to be used in uncontrolled environmental conditions such as in outdoor applications or in space; the temperature control is not an option. The other approach to this problem is to tune the biasing voltage or SiPM dark current with changing conditions.

*SiPM Dark Current Control*

In [15], it is shown that the relation between dark current of SiPM and temperature can be approximated to exponential function which is similar to behaviour of thermistor. Therefore, the gain of SiPM can be stabilized by using thermistor to compensate for changes due to temperature variations by indirectly controlling the biasing voltage that will appear across SiPM. But this approach is limited to small range temperature changes and drifting of amplifier gain is possible at temperature variations outside the range. The temperature variation of -5% /˚C, in the range of -18˚C to -8˚C, was minimized to a value of 0.3% /˚C.

As the dark current of SiPM is a function of bias voltage and vice versa, the gain can be stabilized by controlling current that flows through SiPM. This approach is explored in [16] by designing a voltage controlled current sink using NTC thermistors that can control the current flowing through SiPM. But this approach is limited to low intensity of light and around room temperature applications where photon rate is smaller than dark count rate. Controlling the dark current through SiPM is a difficult task and makes the system more complex. But the gain variation is reduced to 6% in the temperature range of 5.1 ˚C to 33.3 ˚C.

*Bias Voltage Control*

Another approach is to control the biasing voltage directly [17] so that the effects of temperature variations can be compensated. This approach is relatively less complex than controlling dark current. In [17], a temperature to voltage converter module is used to control the bias voltage of SiPM. Fig. 4 shows the block diagram of the scheme. This scheme controls the bias return potential according to temperature variations to control the apparent bias voltage across SiPM, so that the over-voltage applied will be constant for achieving constant gain condition. In 3˚C temperature change, gain variation of about 33% without compensation is reduced to 1% with passive compensation circuit.

A variation to the scheme in [17], is proposed by Licciulli et al., in [18]; which uses a blind SiPM as a temperature sensor for correcting the biasing voltage of other light sensitive SiPMs as shown in Fig. 3. In [18], a SiPM with no incident light (blind SiPM) is used as a temperature sensor and its gain is monitored by measuring the amplitude of output dark pulses. This temperature detector is included in a negative feedback loop which modifies the bias voltage automatically so that the amplitude of dark pulses remains constant, which will in turn keep the gain constant. The advantage of using this scheme is that it will correct the biasing voltage irrespective of knowledge of SiPM parameters. Only thing is that the parameters of blind SiPM and light sensitive SiPM should match. But the biggest disadvantage of this scheme is that it is very complex to implement. The change of 10% dark pulse amplitude variation was reduced to 2% in 20˚C to 30 ˚C temperature range.

The approaches discussed in [15-18] uses a control of bias voltage or dark current using an operational amplifier based circuits to correct the bias voltage using temperature sensor feedback, but this increases the complexity of biasing circuit and limited to temperature variations around room temperature. A. Gil et al. [19] proposed slightly different approach that controls the external power supply. A high resolution DAC is used for controlling the high voltage supply output which supplies bias voltage. A high resolution ADC is used for feedback purpose and all control action of ADC and DAC is done with help of a micro-controller, which also reads the temperature from temperature sensor. The gain variations of 27% are reduced to 0.5% in the temperature range of 20 ˚C to 30 ˚C.

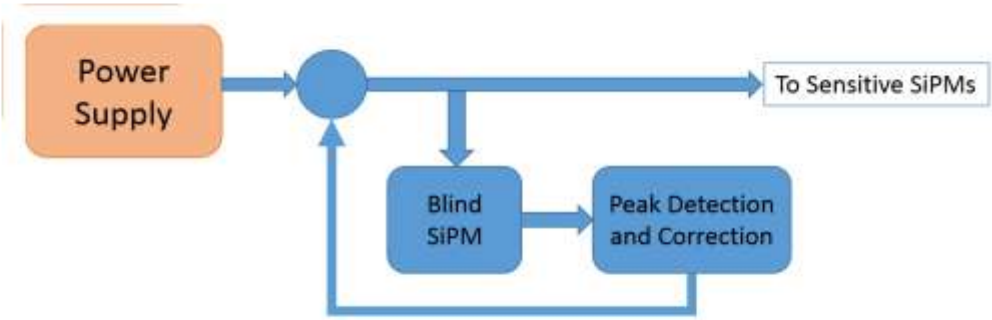


Fig. 3 A blind SiPM as a temperature sensor for correcting biasing voltage

In [20], the relation between gain, temperature and bias voltage is represented in the form of an equation and an external feedback system is implemented using LabVIEW. This system takes the temperature input from a resistance thermometer attached to SiPM assembly and gain input from SiPM data acquisition system. The corrected biasing voltage is calculated depending on the two inputs to LabVIEW system and accordingly the power module is controlled to give corrected biasing voltage. The gain deviation of maximum 1% is achieved in the temperature range of 0˚C to 40 ˚C in this approach.

An extension of system in [20] is presented by same authors in [21], where a self-calibrating gain stabilization method is used for multiple SiPMs. The parameters for stable gain operation are found for one or few SiPM's from a group of SiPM's and these parameters are applied to all detectors in the group. When any of the SiPM does not have same parameters, the gain of that SiPM is different. The system then recalculates the parameters for only those SiPM's whose gain is not matched with the gain of the calibrated SiPM's such that the gain of all detectors is constant. The calibration process is triggered each time the temperature changes. The value of gain does not differ by more than 1% from the set value [21]. This method is useful in systems where large number of detectors are present and it can reduce the calibration process time significantly. Another advantage is that, one need not know the parameters of all detectors; the parameters of only one or few detectors from the group of same detectors will be sufficient for operation of such large systems.

*Temperature Control*

Controlling the biasing voltage according to temperature variations works for keeping the gain constant, but the noise levels of SiPM also increases with increase in temperature and also drifting of amplification gain of SiPM pulse amplifier is also possible. The low value of Signal-to-noise-ratio (SNR) will result in poor energy resolution and errors in event localization of scintillator based systems [22]. However, cooling of SiPM results increase in SNR and energy resolution by SiPM. In [22] a recirculating cooled clear optical liquid is inserted between two optical windows of SiPM resulting in cooling and light conduction in one module. This method is efficient for increasing the SNR of SIPM output, but at the same time it is useful for keeping the gain constant by controlling the temperature. More research is going on in cooling the SiPM structure itself.

The use of Peltier cooler for maintaining the SiPM temperature is demonstrated in [23]. The temperature control of approximately 10˚C can be achieved by using Peltier cooler. A complete multichannel SiPM power supply is designed [23] which can be used for 18 SiPM channels simultaneously. This supply can regulate the output voltage from 0V to 100 V and can supply 100 µA current per channel. The output voltage is settable with a resolution of 25 mV with stability of 5 mV. This type of supply is useful for multi-channel systems where multiple SiPM detectors are required to work simultaneously.

## V. CONCLUSION AND DISCUSSION

The power supply approaches discussed in section II and III are available commercially but main disadvantage is that the whole unit can be used with single SiPM channel and the cost of instrument will be very high. A custom power supply unit [23] with multiple channels capability at relatively lower cost than commercially available options is the way ahead. The control of bias voltage (or dark current) of SiPM with respect to temperature can be implemented in this custom power supply unit with help of temperature sensor and a controlling device like micro-controller or FPGA. A complete feedback system will be possible for control of biasing voltage of SiPM with respect to varying temperature conditions. This approach will help to prove SiPM as a more accurate sensor and suitable for use in different environmental conditions.

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