

A shot-noise limited 420 Mbps visible light communication system using commercial off-the-shelf silicon photomultiplier (SiPM)

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Abstract—A commercial off-the-shelf silicon photomultiplier (SiPM) has been incorporated into a photon counting VLC receiver. In order to minimize the number of background counts in 500 lux of ambient light this receiver is used in conjunction with a 405 nm transmitter, specifically a laser diode. Data was transmitted over the resulting link using on-off keying and a bit-error-rate (BER) of less than 10^{-3} was achieved for data-rates greater than 420 Mbps. Furthermore, these data rates were achieved with received optical powers of 10 nW (−50 dBm). This means that they are orders of magnitude more sensitive than receivers that use PIN photodiodes.

Keywords—silicon photomultiplier (SiPM), avalanche photodiode (APD), Geiger-mode avalanche photodiode (GM-APD), single photon avalanche photodiode (SPAD), multi-pixel photon counter (MPPC), visible light communication (VLC)

I. INTRODUCTION

Like all communications systems, the capacity of visible light communication (VLC) systems depends upon the bandwidth of the channel and the signal to noise ratio (SNR) at the output of the receiver. Until recently the only available photodetectors were avalanche photodiodes (APDs) and PIN photodiodes. Typically, the signal to noise ratio of PIN photodiodes is limited by the noise from the other electronic components in the receiver, often a transimpedance amplifier. In contrast, APDs work at higher biasing voltages and have an internal gain, created by avalanche multiplication which means that APDs can be used to increase the sensitivity of receivers. However, the avalanche multiplication also creates a bias dependent excess noise which means that the best performance is achieved when the gain is limited, typically to a value less than 100. The problems associated with excess noise can be avoided if the APDs are operated above their breakdown voltage, i.e. in the Geiger-mode, and placed in series with a device that quenches the self-sustained avalanche current. This combination of APD and quenching device can be used to detect single photons and is therefore referred to as a single photon avalanche diode (SPAD). A single SPAD could be used in a receiver, however, SPADs need time, typically a few ns or longer, to recover from each detected photon and since even an ideal photon counting receiver needs to detect a few photons per bit the data rate of a

receiver containing a single SPAD would be limited. This limitation can be overcome using an array of SPADs operating in parallel within devices that are sometimes known as silicon photo-multipliers (SiPMs) or multiple-pixel photon counters (MPPCs). Previously, the performance of several SPAD-based VLC receivers have been reported [1]–[11] and recently it has been suggested that SiPMs/MPPCs with photon detection efficiencies (PDEs) greater than 14% could be used to create receivers that are more sensitive than existing receivers based upon APDs [9].

Recently SiPMs have become available that can have PDEs of more than 40% in the blue part of the visible band spectrum. They also have 1.5 ns output pulses [12] that are significantly shorter than the output pulses of other commercially available SiPMs or MPPCs. These short output pulses suggest that they should be able to operate at OOK data rates well over 100 Mbps without significant ISI. However, the individual SPADs in SiPMs/MPPCs still have other non-ideal behaviours, including dark counts, after-pulsing and optical cross-talk [13–14], that together with ambient light could degrade their sensitivity. The challenge is therefore to achieve these relatively high data rates whilst maintaining a sensitivity limited by the unavoidable statistical noise, known as shot or Poisson noise.

The rest of the paper is organized as follows. The operation of a SiPM and the sensitivity of an ideal photon counting receiver are discussed in section II. The device characterisation results, such as PDE, dark counts, and maximum count rate, for the particular SiPM that has been used in a communications link are presented Section III. The performance of a receiver containing this SiPM is then described in Section IV. Conclusions are given in Section V.

II. UNDERLYING CONCEPTS

As shown in the schematic diagram in Fig.1 a SiPM consists of an array of identical elements known as μ cells, that each contain an APD in series with a quenching resistor, R_Q . The node within each μ cell between the APD and R_Q is capacitively coupled to a common output node. These μ cells are also connected in parallel to a common voltage that is used to bias the APDs above their breakdown voltage. This bias voltage means that when a photon generates an electron-hole pair in an APD these charge carriers will initiate an

avalanche process and a relatively large current will flow in the APD. However, this current must also flow through R_Q and the resulting decrease in the bias voltage across the APD quenches this avalanche current. A current then flows through R_Q , which recharges the capacitance of the APD and hence increases the bias voltage across the APD. Since this recharging process takes a finite time there is a dead time after each photon is detected [15]. In addition to any electron-hole pairs generated by photons, there are also electron-hole pairs generated by thermal excitation which also generate output pulses [15]. Since thermal excitation continues in the dark, these pulses occur in the dark and are therefore known as dark counts.

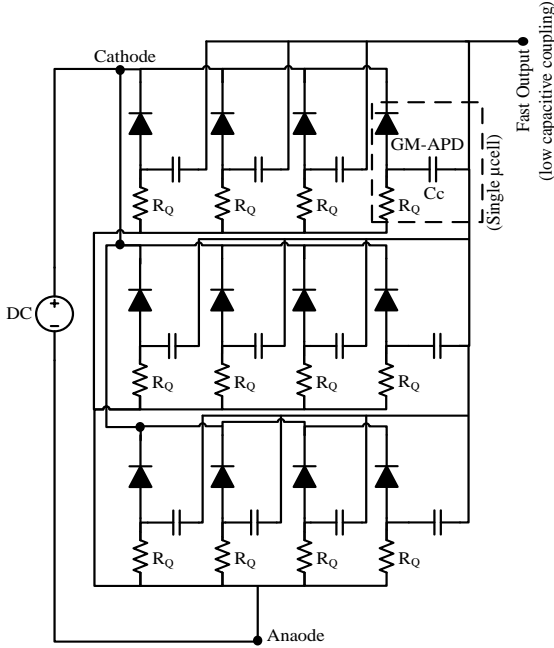


Fig. 1. The simplified schematic diagram of the ON Semiconductor J-series SiPM. Unlike standard SiPMs, these SiPMs have a capacitive coupling each μ cell to a common output.

In the ON Semiconductor J series of SiPMs the changes in voltage within a μ cell are capacitively coupled to the shared output of the SiPM. If two or more photons are concurrently absorbed by two or more different μ cells the current pulses from each μ cell sum together on the shared output. Since the output pulses can be designed to be much larger than noise in subsequent electronics a SiPM can be used to create a photon counting receiver.

In a photon counting receiver, the dominant noise is shot or Poisson noise. This means that the signal needed to achieve a particular BER when OOK is used to transmit data can be calculated using [1]

$$BER = \frac{1}{2} \left[\sum_{k=0}^{t_h} \frac{(n_s + n_b)^k}{k!} \times e^{-(n_b + n_s)} + \sum_{k=t_h}^{\infty} \frac{n_b^k}{k!} \cdot e^{-n_b} \right] \quad (1)$$

where n_s is the number of counts per symbol time when a one is being transmitted and n_b is the number of counts per symbol time when a zero is being transmitted. Both of these numbers include the dark counts in the SiPM and the counts arising from photons from the background light. In addition,

n_b can include counts from photons emitted by the transmitter when it is transmitting a zero.

Fig.2 shows the required number of signal counts per symbol required to achieve a BER of 10^{-3} for a range of background counts calculated using (1). The results in Fig. 2 show that the number of detected signal photons per bit required to achieve this BER increases less rapidly than the number of background counts per bit. Despite this observation in order to maximize the sensitivity of the receiver, the number of background counts per bit should be limited wherever possible. In particular, the transmitters output power when transmitting a zero should be minimized. In addition, the wavelength used to transmit data should be selected to limit the intensity of the background light as much as possible.

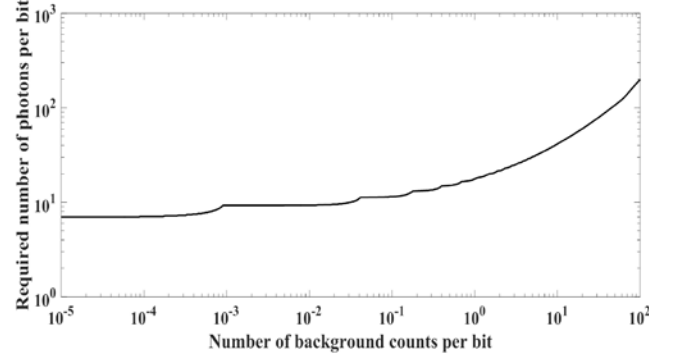


Fig. 2. The required number of photons per bit vs. the number of background counts to achieve a target BER of 10^{-3} using OOK modulation.

To allow for operation in an office or home a VLC receiver must be able to operate in the presence of ambient light and the spectrum of ambient light should be considered when selecting a suitable wavelength use with a SiPM receiver. Since white LEDs are rapidly replacing other light sources, the spectra of white LEDs have been considered. Both cold and warm white LEDs have two regions in which they emit relatively little light. The first region is wavelengths shorter than 410 nm and the second region is wavelengths longer than 740 nm. This suggests that a good choice of transmission wavelength is one shorter than 410 nm or longer than 750 nm. The data sheet for the ON Semiconductor J series SiPMs that have a fast output pulse show that they have a PDE of less than 7% at 750 nm and a PDE of more than 35% at 410 nm. Even taking into account the different energies of photons at these two wavelengths the shorter wavelengths are therefore a better option. Within this range of wavelengths the PDE of these SiPMs decreases at shorter wavelengths. Furthermore, a relatively inexpensive laser diode, the L405P20, with a peak emission wavelength approximately 405 nm is available. This laser diode was therefore chosen as the transmitter.

III. DEVICE CHARACTERISATION

The SiPM with a fast output pulse and relatively high PDE in the blue region that has been used as the photodetector in the receiver is the J-series SiPM, which consists of 5676 SPADs connected in parallel and an active area of 3.07 mm by 3.07 mm. As with all SiPMs and MPPCs the bias voltage applied to this SiPM determines several important characteristics including the PDE, the dark count rate, the probability of after-pulsing and the probability of optical cross-talk. The datasheet of the J-series devices gives the

probabilities of after-pulsing and cross-talk at two bias voltages. In particular, at a bias voltage of 27 V the cross-talk and after pulsing probabilities are equal to 8% and 0.75% respectively, whereas, at 30.5 V the cross-talk and after-pulsing probabilities are 25% and 5% [12]. In order to reduce the significance of these two non-idealities experiments were performed at a bias voltage of 27 V. As recommended by the manufacturer the fast output of the SiPM was connected to a ZFL1000-LN+ Mini-circuits amplifier during all experiments.

In order to measure the dark count rate the SiPM was placed in the dark and the resulting output pulses were captured using a HDO6104-MS Lecroy 1 GHz oscilloscope and counted. The measured dark count rate of the particular SiPM in our laboratory, biased at 27 V, was found to be approximately 800 kcps. At data rates of more than 100 Mbps, this corresponds to fewer than 10^{-2} photons per bit and results in Fig. 2 show that in the dark, a BER of 10^{-3} should be achievable with 10 photons per bit.

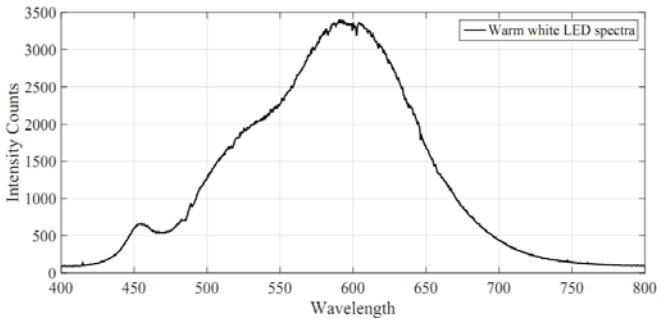


Fig. 3 The spectrum of the warm white LED used to generate the ambient light in the experiments described in this paper, measured using ocean optics spectrometer (SD2000).

In order to reduce the number of photons required to transmit data in ambient light the amount of ambient light reaching the SiPM was reduced using an FB405-10 optical bandpass filter with a centre wavelength of 405 ± 2 nm and a FWHM of 10 ± 2 nm. In addition, an iris was used to restrict the field of view of the SiPM. With these precautions, the measured background count rate in 500 lux generated by a white light LED, whose spectrum is shown in Fig. 3, was 370 Mcps.

The data sheet of the L405P20 shows that the centre wavelength increases by 0.1 nm when the laser diodes temperature increases by one degree centigrade. To ensure that the centre wavelength stays within the pass band of the FB405-10, thermal paste was used to ensure good thermal contact between the laser diode and the supporting S1LM56 optical mount. In addition, the L405P20 was cooled using a $60 \times 60 \times 25$ mm axial fan next to the laser diode. With these precautions when the laser diode is at thermal equilibrium the centre wavelength measured using an SD2000 Ocean Optics spectrometer was 404 nm.

Although a SiPM isn't blinded by the dead-time the existence of a dead-time can create a non-linear response, which is a function of the PDE of the SiPM, the total number of μ cells and the dead-time of each μ cell. The impact of the non-linear response has been calculated using the paralyzable dead-time model [16-17],

$$N_{measured} = N_{det_{ideal}} \times \exp\left(\frac{-N_{det_{ideal}} \times \tau_{dp} \times \beta}{N_{SPADs}}\right) \quad (2)$$

In this equation τ_{dp} is the paralyzable dead time which equals $5\tau_{RC}$, where τ_{RC} is the RC time constant which is 32 ns for this SiPM [12], [14], [18]. The term β in this equation then represents the fraction of the paralyzable dead-time during which a photon cannot be detected.

To measure the response of the SiPM a wire grid polariser was used to vary the output power from the laser diode. The resulting output power at the location of the SiPM was then measured using an 818-SL calibrated photodiode and a Newport 1830-C optical power meter. The number of counts per second at a number of different optical power levels were then determined from the signal captured using the HDO6104. The measured numbers of detected photons per second at different optical power levels are shown in Fig. 4. The linear response shown as a dashed line in Fig. 4 corresponds to an effective PDE of 25%. This is lower than the value in the datasheet because this measurement includes the effect of the FB405-10. In addition Fig. 4 includes a solid line which represents the best fit between the experimental results and (2). This best fit corresponds to $\beta=0.44$, which means that the minimum time between detectable photons is 70.4 ns. The results in Fig. 4 also show that the number of counts per second saturates at approximately 30 Gcps when the incident optical power is greater than 80 nW.

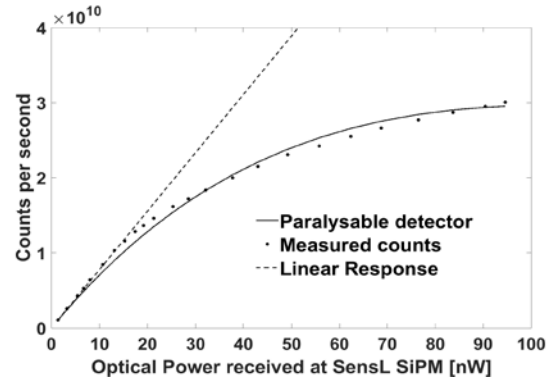


Fig. 4. ON Semiconductor J-series measured counts as a function of incident optical power compared to a linear response and the expected response of a paralyzable detector. Saturation of measured counts occurs after 80 nW count rate.

IV. PERFORMANCE EVALUATION

A schematic diagram of the experimental setup used to test the performance of the ON Semiconductor SiPM as a VLC receiver is shown in Fig. 5. The transmitter section of the experiment consists of 10 GHz Tektronix arbitrary waveform generator (AWG), which outputs a pseudorandom binary sequence (PRBS). This AWG generates a maximum peak-to-peak voltage of 500 mV and so an amplifier was required to amplify the AWG output signal by a factor of 8 to drive the laser. Then, since the laser diode cannot be operated in reverse bias, a Mini-Circuits Bias-Tee (ZFBT-4R2GW+) was used to add a 3 V d.c. bias to the RF signal. The combined signal, which was designed to ensure that the laser diode was off when transmitting a zero, was then applied to the L405P20 laser diode which transmits the data to the ON Semiconductor SiPM. In order to control the amount of laser light falling on the SiPM a wire optical polariser was placed in front of the laser diode.

The receiver section of the experiment consists of a FB405-10 optical bandpass filter, an iris and a SiPM which

receives the optical signal transmitted from the laser diode. The fast output of the SiPM was connected to a HDO6014-MS Lecroy oscilloscope, that captures the received signal, via a ZHL-6A+ amplifier.

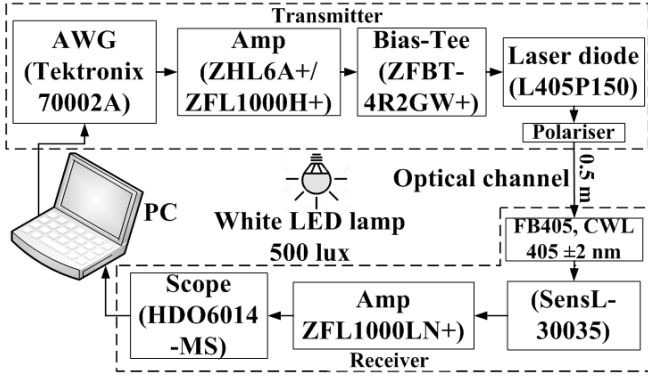


Fig. 5. Block diagram of the experimental setup used to test the ON Semiconductor J-series 30035 for the communication.

An optical link of distance 50 cm separates the transmitter and the receiver. The white LED, whose output spectrum is shown in Fig. 3, was placed behind the transmitter ensured that the SiPM was illuminated with 500 lux of white light. The AWG and the scope are both controlled by a PC, which processes the received signal using a MATLAB script to calculate the BER.

The performance of the receiver was evaluated at different data rates from 100 Mbps to 660 Mbps for a target BER of less than 10^{-3} . To test the performance of the receiver, a PRBS data of length 2^{15} at 100 Mbps, 2^{16} at 200 Mbps, 2^{16} at 300 Mbps, and, 2^{17} at 400 Mbps and above was transmitted in a single frame of data. For each data rate, the PRBS data is transmitted 20 times, with a different sequence being transmitted each time and an average BER was calculated. At each data rate, the polariser was used to vary the optical power needed at the SiPM to obtain the target BER.

Initially, the experiments were performed with a Mini-Circuits 500 MHz amplifier (ZHL-6A+) which has a lower frequency of 2.5 kHz. Using this amplifier, the PRBS data was transmitted at data rates up to 500 Mbps. The results in Fig. 6 show that when this amplifier is used the number of detected photons per bit agrees with the number of photons per bit for a shot-noise limited system, estimated using (1). This means that at a data rate of 400 Mbps a BER of 10^{-3} was achieved with 16.3 detected photons per bit, which corresponds to a sensitivity of -51 dBm. This SiPM is therefore slightly more sensitive than a CMOS SPAD receiver system-on-a-chip [11].

A clear feature of the results in Fig. 6 is that the number of detected photons per bit required to achieve the target BER increases rapidly for data rates higher than 400 Mbps. A possible cause of this increase is the limited bandwidth of the ZHL-6A+ amplifier. This amplifier was therefore replaced by a ZFL1000H+ amplifier from Mini-circuits which has an upper frequency of 1 GHz and a lower frequency of 10 MHz. The lower frequency of this amplifier was expected to introduce significant baseline wander and therefore whenever it was used data was transmitted using 8b10b encoding [19], [20], [21]. The results in Fig. 6 show that this change of amplifiers changed the number of detected photons per bit needed to achieve a BER of 10^{-3} at data rates above 420 Mbps. For example, with the 1 GHz amplifier, it requires 17.7 detected photons per bit to achieve

a BER of 10^{-3} at 500 Mbps. Taking into account the SiPMs PDP this corresponds to an average received power of -50.6 dBm. Since the transmitter and amplifier bandwidths are too high to cause ISI at 500 Mbps the increase in the required number of detected photons per bit above 500 Mbps is probably due to the finite output pulse width of the SiPM, which is 1.5 ns.

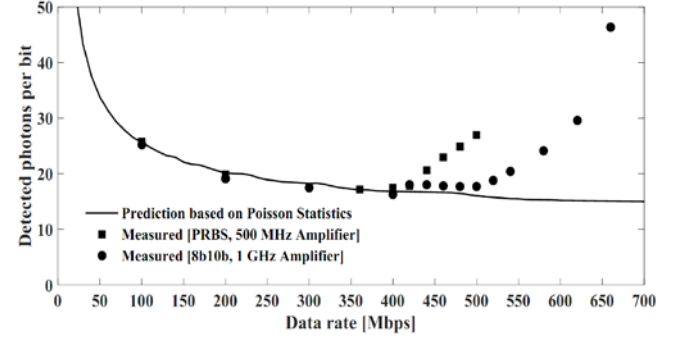


Fig. 6. The required and measured number of photons vs. the data rate to achieve a target BER less than 10^{-3} using OOK modulation. The receiver performance is compared with the shot-noise limited system in the background illumination of 500 lux.

The power required to transmit 500 Mbps to the SiPM is approximately 10 nW, which corresponds to 1 mWm^{-2} . If the SiPM didn't cause ISI then, since the number of detected photons per bit needs to remain the same so that a target BER can be maintained, these results suggest it would need approximately 20 nW or 2 mWm^{-2} to support 1 Gbps. However, the finite output pulse width of the SiPM will mean that ISI will be significant at this data rate and equalization will be required. This equalization will require additional optical power, however, if this data rate can be achieved whilst avoiding saturating the SiPM the SiPM receiver will be between 3 and 4 orders of magnitude more sensitive than a receiver based upon a PIN photodiode [22].

More importantly, the sensitivity of the SiPM receiver could have a significant impact on some types of VLC system. For example if the end of a 1mm POF with an NA of 0.5 is employed as a transmitter then the eye safe limit at 405 nm is 30 mW and a receiver incorporating an SiPM would then enable this transmitter to transmit 500 Mbps and cover an area of up to 30 m^2 [23].

V. CONCLUSION

The sensitivity of a SiPM based receiver is determined by a combination of its PDE and the number of background counts. Results have been presented which show that when the wavelength used to transmit data is selected carefully, the light incident on the receiver is filtered and the receiver FoV is restricted, the dark count rate of the SiPM is negligible. Further experimental results have been presented which show that the performance of a receiver containing a J-series SiPM can be predicted assuming that it functions as an ideal photon counting receiver at data rates up to 420 Mbps. Finally, the results at 420 Mbps have been used to estimate the optical power need to transmit 1 Gbps to this receiver using equalisation to overcome ISI caused by the duration of the SiPM's output pulses. This estimate leads to the conclusion that this SiPM based receiver will be between 3 and 4 orders of magnitude more sensitive than a receiver based upon a PIN photodiode. It is possible that the high sensitivity of SiPM receivers will enable them to receive signals from transmitters formed by the end of a 1 mm POF.

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