A SiPM-based VLC Receiver for Gigabit communication using OOK Modulation

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***Abstract*—- The growing demand for wireless communications services means that RF systems are increasingly unable to support user's requirement. Consequently, there is a growing interest in using visible light communication (VLC), including interest in sensitive VLC receivers. Since they have the potential to detect single photons, silicon photomultipliers (SiPMs) could potentially be used to create the most sensitive possible VLC receivers. In this paper, results of experiments to determine the optimum bias voltage and dynamic range of an off-the-shelf SiPM are reported. Results are then presented which show that in 500 lux of ambient light this receiver supports data rates of more than 2 Gbps with a bit-error-rate (BER) of 10^{-3}.**

***Index Terms*— Silicon photomultiplier (SiPM), single-photon avalanche photodiode (SPAD), visible light communications (VLC), optical wireless communications (OWC).**

I. Introduction

VISIBLE light communications (VLC) is currently being investigated as a technology that could be used to complement WiFi in future heterogeneous communications networks. As with all communications systems, the channel capacity of a VLC system depends upon the signal to noise ratio (SNR) of the received signal. Unfortunately, when a photodiode is used in a receiver the receiver's noise is dominated by electronic noise. The impact of this noise can be reduced by amplifying the photocurrent in the photodetector using avalanche multiplication within an avalanche photodiode (APD). However, avalanche multiplication creates excess noise in the APD and the best SNR is obtained when the gain from avalanche multiplication is limited. Any limitations associated with excess noise can be avoided by biasing the APD above its breakdown voltage and placing it in series with a device that quenches the resulting self-sustained avalanche current. This combination of APD and quenching device can be used to detect single photons and it is therefore referred to as a single-photon avalanche diode (SPAD). In the past few years, several different types of VLC receiver that incorporate SPADs have been proposed [1]–[9].

A potential drawback when using SPADs is that they need a finite time, typically a few nanoseconds, to recover from each detected photon. The potential problems associated with this recovery or dead time can be overcome using an array of SPADs. However, in addition to the recovery time, arrays of SPADs have other non-ideal behaviors including dark counts, after-pulsing, optical cross-talk and a finite output pulse width [10]. Despite these non-ideal behaviors some impressive results have been obtained. For example, recently, results from a 2.8 mm by 2.6 mm custom SiPM containing 4096 SPADs and associated circuitry have been reported [7]. When OOK modulation and decision feedback equalization (DFE) was used this receiver could operate at 400 Mbps with a BER of 1.8×10^{-3} when the received irradiance was 1.4 mWm^{-2}. This corresponds to a sensitivity of –49.9 dBm, which is 13 dB higher than the Poisson limit. More recently, a commercially available 3.07 mm by 3.07 mm array of passive quenched SPADs, known as a silicon photo-multiplier (SiPM), has been incorporated into a VLC receiver. When operating in 500 lux of ambient light, and without any equalization, this receiver's sensitivity was limited by Poisson noise for OOK data rates up to 400 Mbps [8]. Consequently, a BER of 10^{-3} was obtained at 400 Mbps with a received irradiance of 0.48 mWm^{-2}. This is equivalent to a sensitivity of –53.4 dBm, which is 8.7 dB higher than the Poisson limit. The commercial SiPM is therefore slightly more sensitive than the custom device [2]. More importantly, at these data rates both of these receivers are more sensitive and closer to the Poisson limit than the linear APD receivers in a recent survey [9].

In this paper, the operation of a SiPM and experiments to optimise the bias voltage of the SiPM are described in section II. This is followed, section III, by a description of experiments to determine the dynamic range of the SiPM. Results in section IV show that it is possible to transmit 2.4 Gbps to the SiPM. Section V contains concluding remarks.

II. SiPM Operation and Bias Optimisation

A SiPM is an array of passive quenched SPADs, each of which is referred to as a microcell (µcell). The 3.07 mm by 3.07 mm J series SiPM manufactured by ON Semiconductor used in the experiments described in this paper contained 5676, 35 µm µcells with a fill-factor of 75%. Each of these µcells contains an APD, with a breakdown voltage of 24.5 V, operated above its breakdown voltage and connected in series with a quenching resistor R_Q. When an electron-hole pair is generated

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in the depletion region of the APD an avalanche current flows through R_Q. The resulting decrease in the voltage across the APD quenches the avalanche process. R_Q then recharges the capacitance of the APD in 45 ns so that it is again biased above its breakdown voltage [11]. In a J series SiPM, all the µcells share a bias connection through which all the current pulses caused by the avalanche events flow. In addition, in the J series SiPMs, the connection between the APD and R_Q in each µcell is capacitively coupled to a second shared output. This coupling means that any change in the bias voltage of an APD creates a fast pulse on this second shared output, which has a full-width at half maximum of 1.5 ns.

Since SiPMs can detect individual photons they have the potential to be used to create receivers whose performance is limited by unavoidable Poisson or shot noise. If this is the case then the number of detected signal photons per bit, n_s, needed to obtain a target BER in the presence of n_b background photons per bit can be calculated using

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

The probability that a photon will be detected is characterised by the SiPM's photon detection efficiency (PDE). This important characteristic of a SiPM is zero until the bias voltage is high enough to initiate avalanche events. Once avalanche processes can be initiated the PDE increases as the bias voltage increases. However, both the datasheet and our experimental results show that the PDE gradually approaches an asymptotic value once the bias voltage is more than approximately 27.5 V. Consequently, with a bias voltage of 30.5 V the PDE at 420nm is 50% and it is more than 25% between 300 nm and 560 nm. This behavior suggests that the SiPM should be operated at the highest possible bias voltage. Unfortunately, as the bias voltage increases the probability that a thermally generated electron-hole pair will create an avalanche event also increases. The resulting dark counts contribute to the number of background counts per bit and they can, therefore, cause an increase in the number of signal counts per bit. The impact of variations in PDE and the dark count rate (DCR) on the optical power at the SiPM needed to achieve a BER of 10^{-3} has therefore been investigated.

A schematic diagram of the experimental setup used to investigate the impact of varying the SiPM bias voltage is shown in Fig. 1. In this experimental set-up, the transmitter consisted of a 10 GHz Tektronix arbitrary waveform generator (AWG), which generated a pseudorandom binary sequence (PRBS).

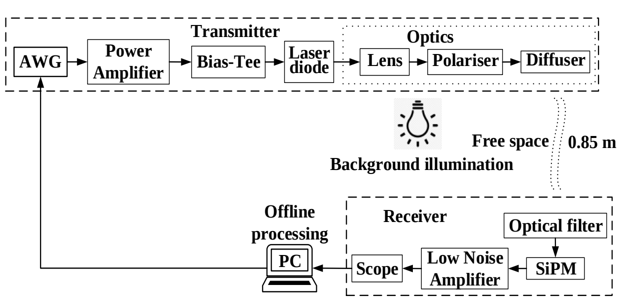

Fig. 1. System block diagram describes the experimental setup used to evaluate the performance of the selected SiPM

Since the maximum peak-to-peak output voltage from this AWG is 500 mV, a Mini-Circuits ZFL-1000H+ amplifier was used to amplify the AWG output signal so that it was large enough to modulate a laser diode. Once amplified the AWG output was combined with a DC bias voltage by a Mini-Circuits Bias-Tee (ZFBT-4R2GW+). This combined signal was then applied to a L405P20 laser diode that has a peak output wavelength of 405 nm. This particular wavelength was chosen because it close to the wavelength at which the SiPM has its maximum PDE which also corresponds to relatively low levels of ambient light in offices. In order to controllably vary the irradiance from the laser light falling on the SiPM, an optical polariser was placed in front of the laser diode.

When OOK modulation is used the receiver's sensitivity is maximised when no photons reach the receiver when a zero is being transmitted. To achieve this condition the laser diode was biased with a d.c. bias of 3 V. This bias voltage was then modulated with a 4 V peak-to-peak a.c. voltage. To replicate normal operating conditions the receiver could also be illuminated by a warm white LED. When this LED was turned on it provided 500 lux of ambient to the SiPM.

The receiver in the experiment consisted of a Thorlabs FB405-10 optical filter, centred at 405 ± 2 nm and a FWHM of 10 ± 2 nm, which rejected most of any ambient light, the J series SiPM and a ZFL-1000LN+ amplifier on the fast output of the SiPM. This amplifier amplified the output pulses from the SiPM before they were captured by a Keysight MSOV334A 33GHz, 80 GSps oscilloscope.

Previously results of experiments with this experimental set-up and a SiPM bias voltage of 27 V have been reported [8]. An important aspect of these results was that data rates of up to 500 Mbps were achieved when the measured number of photons per bit agrees with the number of photons per bit estimated using (1). Furthermore, this Poisson noise limited performance was achieved without equalization at an irradiance of 0.6 mWm^{-2}.

Previous results had shown that it is possible to transmit 400 Mbps with a BER of 10^{-3} to the SiPM without significant ISI. Consequently, at this data rate, the irradiance required to transmit data was determined by the PDE of the SiPM and the number of background counts per bit. Both the PDE and the DCR increase with bias voltage. However, for a system limited by Poisson noise they have opposite effects on the irradiance needed to achieve a target BER. The irradiance needed to achieve a BER of 10^{-3} at 400 Mbps has therefore been measured for different bias voltages. The results of these experiments are shown in Fig 2. In addition, this figure shows the irradiance required to achieve this BER predicted using (1) and the bias dependence of the PDE and DCR. Unexpectedly, the experimental data showed an optimum bias voltage that was not predicted. However, dark counts are not the only non-ideal behaviour of SiPMs. In addition, defects within the avalanche region of each µcell can temporarily trap a charge which creates an avalanche event, known as an after-pulse, after an observable delay. Furthermore, photons generated by recombination in one µcell can initiate avalanche events in another µcell, a process known as optical cross-talk. The impact of these two phenomena on the background counts per bit has been calculated using the measured probabilities of the occurrence of after-pulses and optical cross-talk [12]. However, these

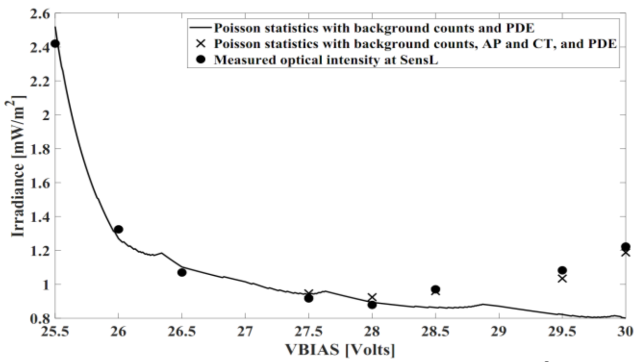

Fig. 2. Irradiance at the receiver needed to achieve a BER of 10^{-3} at 400 Mbps at various bias voltages. The experimental data are compared to both irradiance required predicted based upon the dark counts and photon detection efficiency. In addition it is compared to the predictions that also include after-pulsing and optical cross-talk

probabilities were only measured at a few bias voltages and so the irradiance equivalent to the Poisson limit can only be calculated using (1) at these bias voltages. The resulting modified estimates of the irradiance corresponding to the Poisson limit in Fig. 2 show that it is the optical cross talk and after-pulsing that create the optimum bias voltage.

A comparison of the probabilities of the two effects at 30 V, 7% for after-pulsing and 23% for direct optical cross-talk, shows that in these devices optical cross talk is the more important of the two phenomena. More importantly, the optimum bias voltage for this device is 28 V and at this bias voltage, the irradiance at the SiPM required to achieve a particular BER can be determined using (1), the DCR of the SiPM and its PDE.

III. Dynamic Range

Another significant non-ideality in SiPM behaviour is the recovery or dead time of each µcell. This non-ideality arises because immediately after the detection of a photon the bias voltage across the APD in the relevant µcell will be too low to initiate an avalanche event. Consequently, any photon that is absorbed in an APD whilst its bias voltage is recovering after a detection event can go undetected. This phenomenon means that once the irradiance on the SiPM is high enough for the average time between photons impacting a µcell to be comparable to the dead time, more of the incident photons are undetected. This means that at high irradiances, the effective PDE of the SiPM will be lower than at low irradiances. Eventually, the SiPM response saturates.

The response of the J series SiPM, with a bias voltage of 28 V, has been tested using the L405P150 laser diode. As in other experiments, the intensity of the light falling on the SiPM was varied using the 34-254 Edmund Optics wire-grid polarizer. When the polarizer angle was changed the irradiance of the diffused laser light falling in the SiPM was measured using a 818-SL calibrated photodiode. The current flowing into the SiPM from its bias voltage supply when it was placed in the same location was then measured using a Keithley 195A digital ammeter.

The results in Fig. 3 show that for irradiances up to approximately 1 mWm^{-2} the current supplied by the source of the SiPMs bias voltage is proportional to the optical power

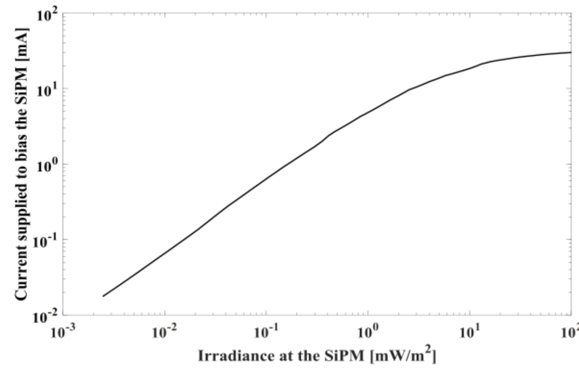

Fig. 3 SiPM dynamic range as a function of irradiance on log-log scale

falling on the SiPM surface. However, the relationship between optical power and this current becomes non-linear when the irradiance at the SiPM is more than 1 mWm^{-2} and it effectively saturates for irradiances higher than 10 mWm^{-2}. Despite this saturation the measured current and the data in Fig. 3 was used to determine the optical power falling on the SiPM in subsequent experiments with the same laser diode.

The current provided by the source of the SiPM's bias voltage recharges the µcells in the SiPM. This means that at irradiances of less than 1 mWm^{-2} the current in Fig. 3 is expected to be proportional to the rate at which µcells are being recharged, i.e. the rate at which photons are being counted. To estimate the maximum count rate which corresponds to the end of the linear region the photocurrent and the individual pulses from the fast output have been measured simultaneously at low optical powers. These results showed that an irradiance of 1 µWm^{-2} corresponds to a current supplied by the source of the SiPMs bias voltage of 7 µA and a photon count rate of 10 Mcps. This last result suggests that the linear region of Fig. 3 ends at approximately 10 Gcps.

IV. Results Obtained With DFE

Without equalization to reduce the impact of ISI, the maximum data rate that could be transmitted to the J series SiPM with a BER of 10^{-3} was 660 Mbps [8]. However, the SiPM's maximum count rate suggests that even higher data rates can be achieved. To determine if higher data rates can be achieved the laser diode was used to transmit 1.5 Gbps to the SiPM. The ac bias voltage on the laser diode was set to 2 V_{pp} and the dc bias voltage was varied. The d.c. bias associated with the minimum BER was then determined and this value, 3.3 V, was used in data transmission experiments. To apply DFE the single bit response (SBR) of the channel was then measured at each transmitted data rate at which experiments were performed. The average single bit response and the measured noise level were then used to estimate the number of taps that might be required. The weights of these taps were then determined using the recursive least squares algorithm, which is an option within the MATLAB DFE function. Once the tap weights had been determined using a training sequence, 20 pseudo-random bit streams, each containing 2^{15} bits, were transmitted. The BER was then calculated using the total numbers of errors and bits.

The measured average irradiances and detected photons per bit required to achieve a BER of 10^{-3} at different data rates when DFE is employed are shown in Fig. 4. These results show

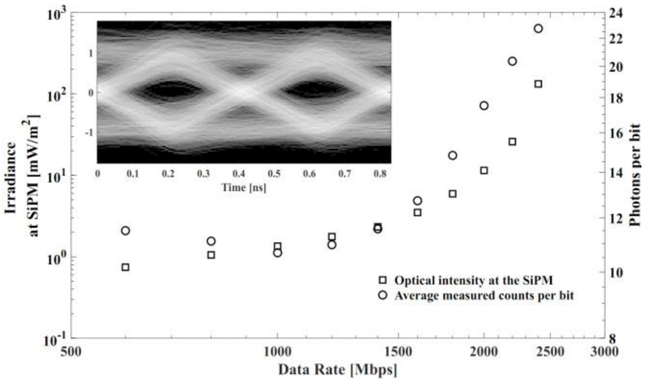

Fig. 4 The measured number of detected photons per bit and average irradiance at the SiPM required to transmit different OOK data rates when the transmitter dc bias voltage has been changed to improve the frequency response of the transmitter. The inset shows the eye diagram at a data rate of 2.4 Gbps after equalization has been applied

a small decrease in the number of photons per bit as the data rate increases from 600 Mbps to 1 Gbps. This small decrease is associated with the reduction in the number of background counts per bit as the data rate increases. However, as the data rate increases above 1 Gbps ISI means that the average number of detected photons per bit approximately doubles from 10.7 at 1 Gbps and 22.7 at 2.4 Gbps.

The relatively small numbers of average detected photons per bit suggest that even higher data rates could be achieved. However, the average optical power data shows that at the higher data rates the SiPM is operating near to saturation. As the data rate increases from 2.2 Gbps to 2.4 Gbps, the SiPM becomes saturated and the irradiance required to transmit data increases very rapidly. This observation makes it clear that the data rate is limited by saturation. Despite saturation, the average optical power at the SiPM required to transmit 2.4 Gbps with a BER of 10^{-3} was only –29 dBm.

For comparison, a state of the art optoelectronic integrated circuit (OEIC) containing an APD achieved a data rate of 2.5 Gbps with a BER of 10^{-3} at a sensitivity of –35dBm [13]. Due to the saturation effect of the SiPM, OEIC is more sensitive than the SiPM at these data rates.. However, as saturation becomes less important at lower data rates, the SiPM becomes significantly more sensitive. As a result, for a BER of 10^{-3} the SiPM and OEIC have comparable sensitivities at approximately 2 Gbps. At a BER of 10^{-3} the SiPM's sensitivity at 1 Gbps (–49 dBm) is approximately 9 dB better than the sensitivity of the OEIC.

V. Conclusion

A 3.07 mm by 3.07 mm ON-Semiconductor J series SiPM has been characterised and used as a receiver in a VLC system. The characterisation experiments showed that the bias dependences of the SiPM's PDE, dark count rate, after pulsing probability and optical cross-talk combined to create an unexpected optimum bias voltage for the SiPM when it is used as a receiver. Further experiments showed that this SiPMs response is linear for irradiances of less than 1 mWm^{-2} or count rates of less than approximately 10 Gcps.

When the bias voltages on the transmitter were optimised to reduce the BER at 1.5 Gbps, and the SiPM receiver operated in 500 lux of ambient light, a data rate of 2.4 Gbps was achieved. This data rate is almost 5 times higher than the previous highest data rate achieved with a receiver that incorporated an array of SPADs. A comparison with a state-of-the-art OEIC containing an APD showed that when the BER is 10^{-3} the SiPM is significantly more sensitive than the OEIC at 1 Gbps. However, at higher data rates the sensitivity of this SiPM is degraded by saturation and the OEIC is more sensitive than the SiPM at 2.5 Gbps.

Since SiPMs are still a relatively new technology it is anticipated that SiPMs will become available that saturate at higher count rates and which are therefore potentially as sensitive as an OEIC at even higher data rates.

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