A 3.45 Gigabits/s SiPM-based OOK VLC Receiver

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Abstract— **A relationship between irradiance and the current needed to maintain the bias voltage applied to a silicon photomultiplier (SiPM) is shown to agree with experimental data. In addition to showing the saturation of the SiPMs response this relationship can be used to determine the power consumed by an SiPM. In addition, results are presented which show that, because of its higher maximum photon count rate, a 30020 SiPM can achieve a bit error rate (BER) of 10^{-3} at a data rate of 3.45 Gbits/s.**

Index Terms—**Visible Light Communications, Optical Wireless Communications, Silicon Photomultiplier, Intersymbol Interference**

I. Introduction

Visible light communications (VLC) is actively being investigated as a technology which could compliment, or in some cases replace, wireless RF communications systems[1]. An important characteristic of any communications system is its maximum data rate, which depends upon the systems bandwidth and the signal to noise ratio (SNR) at the receiver output[2]. An approach to improving the SNR of a VLC receiver that is being investigated is to use a silicon photomultiplier (SiPM). These devices are arrays of microcells, which each contain a single photon avalanche diodes (SPAD). When a photon initiates an avalanche process in a microcell an output pulse is generated and single photons can be detected. The ability to detect photons allows VLC systems to operate within a few photons per bit of the limit determined by Poisson/shot noise. Consequently, at 1 Gbit/s and a BER of 10^{-3}, a SiPM receiver has been shown to have a 9 dB higher optical sensitivity than the best receiver based upon an avalanche photodiode[3]. Unfortunately, after detecting a photon each microcell must recharge. During this recharging or recovery process, which typically last several nanoseconds, a microcell's ability to detect photons is reduced and the response of SiPMs can become saturated[3].

The maximum rate at which a SiPM can generate output pulses depends upon the number of microcells and the microcell recharge or recovery time. The maximum OOK data rate that can be achieved then depends upon the rate at which photons from the ambient light are detected by the SiPM and the required BER, which both influence the number of photons per bit that must be detected, and the amount of inter-symbol interference (ISI) caused by the finite duration of the SiPM output pulses. These various factors mean that the maximum OOK data rate that can be achieved with a SiPM receiver is unpredictable. The relationship between the maximum rate at which output pulses can be generated by a SiPM and the maximum OOK data rate has therefore been investigated.

TABLE I
KEY PARAMETERS OBTAINED FROM THE MANUFACTURES DATA SHEET FOR A J-SERIES 30020 AND 30035 WITH AN OVERVOLTAGE OF 5V [4]

Parameter	30035	30020
Number of Microcells	5675	14410
Microcells active area diameter (µm)	35	20
Fill factor (%)	75	62
Recovery Time constant (ns)	45 ns	15 ns
PDE (405 nm)	0.5 (@ 6V)	0.38 (@ 5V)
Dark Count Rate (MHz)	1.3 (@ 6V)	1.2 (@ 5V)
Pulse width (ns)	1.5	1.4

This paper is organized as follows. The operation and characteristics of SiPMs are discussed in section II. The experimental equipment used to test SiPMs as receivers and the results of experiments are described in sections III and IV. Finally, section V contains concluding remarks.

II. SiPM Characteristics

Silicon photomultipliers (SiPMs) are arrays of microcells that each contain a SPAD. In each microcell a detected photon causes avalanche multiplication and this in turn creates an output pulse which can be counted. Consequently, for data rates less than 400 Mbits/s, receivers that incorporate a SiPM can operate closer to the Poisson or shot noise limit than receivers which contain avalanche photodiodes[3].

Several different SiPMs are commercially available that might be integrated into a VLC receiver. When selecting a SiPM for use as a receiver, multiple device parameters need to be considered. Two of these are the photon detection efficiency (PDE) and the area of the SiPM that mean that lower irradiances are required to support lower data-rates.

At higher data rates, the width of the output pulses generated when a photon is detected can cause ISI and hence the width of the pulses must also be considered. ON-Semiconductor manufactures SiPMs with passively quenched microcells and two outputs. The pulses on the slow output are caused by the

This manuscript was submitted to IEE Photonics Technology Letters on February 8th, 2021. This work has been partly supported by the Punjab Educational Endowment Fund, Pakistan and by the UK Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/R00689X/1.

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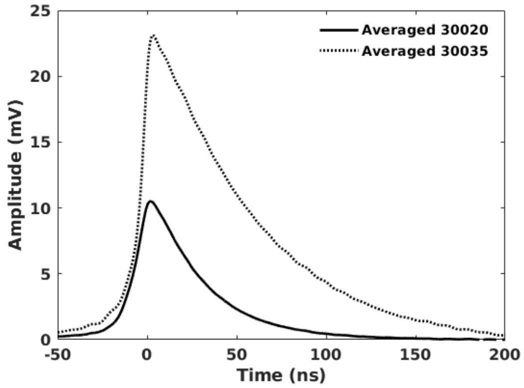

Fig. 1. Mean slow output pulses from a J-30020 and a J-30035 SiPM. The full width half maximum of each pulse is 30 ns and 50 ns respectively, giving characteristic recharge time τ.

current flowing to recharge each microcell after it has been discharged by a photon initiated avalanche process. Unlike other suppliers, ON-Semiconductor manufactures SiPMs with a fast output, which is formed by a capacitive coupling of each microcell to a shared fast output. In order to increase the data rate at which ISI first occurs J series SiPMs from ON-Semiconductor have been used in VLC receivers. As shown in Table 1 the fast output pulse widths of the 30035 and 30020 SiPM devices are similar, 1.5 ns and 1.4 ns, and, since this parameter is their full-width at half maximum, these pulse widths suggest that ISI will start to occur when the OOK data rate is approximately 700 Mbps.

An important feature of SiPMs is that the avalanche process within each microcell must be quenched by reducing the microcell's bias to less than its breakdown voltage. Lowering the bias voltage halts the avalanche event but then the microcell must be recharged. During the time that this recharge or recovery process is taking place the microcell's PDE is reduced and therefore the recovery time is an important characteristic of a SiPM. The recovery time listed in the datasheet, and hence in Table 1, was measured when the SiPM was connected to a 1 Ω resistance. However, the SiPMs used to create receivers were

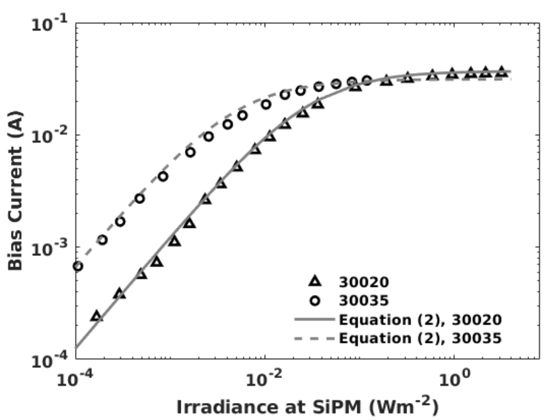

Fig. 2. Variation of the J-30035 and J-30020 SiPM bias currents with irradiance from a 405 nm laser diode when the bias voltage on the SiPM is 27.5V.

mounted on a MicroFJ evaluation board that includes a 50 Ω resistance. The recovery time of the SiPM on the evaluation board was therefore measured by observing the duration of slow output pulses, Fig 1. These pulses showed the expected exponential decay as the microcell recharged with a characteristic time, τ, of 30 ns and 50 ns for the 30020 and the 30035, respectively.

The most important consequence of the recovery time for each microcell is that at high irradiances the time between photons impinging upon each microcell is shorter than the recovery time of the microcell. Consequently, as irradiance increases the probability that a photon is detected reduces until the rate at which photons are detected saturates.

If monochromatic light of wavelength, λ, is incident on a SiPM, then its photon count rate, C_{rate}, has previously been related to the irradiance falling on the SiPM, L, by

$$C_{\mathrm{rate}} = \frac{N_{\mathrm{cells}}\alpha\ (L + L_{\mathrm{dark}})}{1 + \alpha\ \tau_{\mathrm{recharge}}\ (L + L_{\mathrm{dark}})} \tag{1}$$

where $\tau_{\mathrm{recharge}} = 2.2\tau$ is the recharge (recovery) time, whilst N_{cells} and L_{dark} are the number of microcells and the irradiance that is equivalent to the dark count rate of the SiPM[5]. In addition, if $\eta(\lambda)$ is the photon detection efficiency (PDE) of the SiPM at the wavelength of the light incident, A_{SiPM} is the SiPM area and E_p is the photon energy then

$$\alpha = \frac{\eta(\lambda)A_{\mathrm{SiPM}}}{E_p} \tag{2}$$

In order to achieve an acceptable bit error rate several photons must be detected for each OOK bit. Consequently, at data rates of 100 Mbps and higher the count rate of photons from the transmitter is significantly higher than the dark count rate. This means that (1) can be simplified to

$$C_{\mathrm{rate}} = \frac{N_{\mathrm{cells}}\alpha\ L}{1 + \alpha\ \tau_{\mathrm{recharge}}\ L} \tag{3}$$

Then this equation means that the maximum count rate $C_{\max}$, is

$$C_{\max} = \frac{N_{\mathrm{cells}}}{\tau_{\mathrm{recharge}}} \tag{4}$$

This means that the maximum count rates of the 30035 and 30020 when they are mounted onto MicroFJ evaluation boards are 51.6 Gcps and 218 Gcps.

When a photon is detected the associated microcell has to be recharged. If the charge needed to recharge a microcell is Q_{cell} then the current required to maintain the SiPMs bias voltage is

$$I_{\mathrm{bias}} = Q_{\mathrm{cell}}C_{\mathrm{rate}} = \frac{Q_{\mathrm{cell}}N_{\mathrm{cells}}\alpha L}{1 + \alpha\tau_{\mathrm{recharge}}L} \tag{5}$$

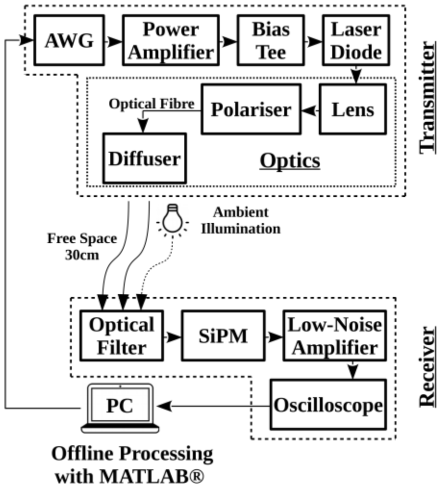

Fig. 3. System block diagram describes the experimental setup used to evaluate the performance of the selected SiPM.

The maximum bias current is then

$$I_{\max} = Q_{\text{cell}} C_{\max} = \frac{Q_{\text{cell}} N_{\text{cells}}}{\tau_{\text{recharge}}} \tag{6}$$

To determine the charge needed to recharge each microcell both the bias current and rate at which fast pulses are generated were measured in the dark for the 30020. Their ratio shows that the charge needed to recharge a microcell is 0.17 pC.

The measured bias currents of a 30020 SiPM at different constant irradiances from a 405 nm laser diode are shown in Fig. 2. This figure also includes the results of equation 5 when the PDE is 0.36. A comparison of these two sets of results shows that (5) accurately predicts the SiPM bias current over a wide range of irradiances. Fig 2 also includes the measured bias current for the 30035 SiPM and the predictions for this SiPM obtained using (5). In this case the PDE of the 30035 was 0.55 and the charge on each microcell was 0.61 pC.

An interesting observation from the results in Fig. 2 is that despite a ratio of maximum count rates of 4.2 the ratio of maximum currents is only 1.18. The smaller charge per microcell of the 30020 therefore makes this SiPM significantly more power efficient than the 30035.

III. Experiment Set-up

A schematic diagram of the experimental setup used to characterize SiPMs receivers is shown in Fig. 3. In this set-up, a 10 GHz Tektronix Arbitrary Waveform Generator (AWG) was used to generate a pseudorandom binary sequence (PRBS) OOK signal. The signal from the AWG was then amplified by a 1 GHz (ZFL-1000H+, 10MHz to 1 GHz) amplifier to produce 2 Vpp signal. However, since this amplifier is not effective at frequencies below 10 MHz, 8b10b coding was used. In order to bias the laser diode to an average current of 48 mA the output signal from amplifier was added to a DC bias voltage by a Bias-Tee (ZFBT-4R2GW+). The combined signal was then applied to a L405P20 laser diode with an output wavelength of 405 nm. (This particular wavelength was chosen because it is close to the wavelength at which the SiPMs PDE is maximum and white light LEDs, which create the ambient light in many situations, have less power at this wavelength than at slightly longer wavelengths). The light from the laser diode was coupled to optics consisting of a lens, polarizer and diffuser. The lens and diffuser were used to create a uniformly illuminated area in which the receiver was placed and the polarizer was then used to vary the irradiance from the laser diode falling on the receiver. In order to replicate operating conditions, the receiver was also illuminated by a warm white LED (a 6W+ 8W Philips IBRS 10461). In the experiments described in this paper this white LED provided 500 lux to the SiPM surface to replicate the worst-case condition which may occur in an office.

The receiver consisted of a SiPM, enclosed in a box. The only optical component used in the receiver was a Thorlabs FB405-10 optical bandpass filter (central wavelength 405 nm and a FWHM of 10 nm), which reduced the amount of ambient light reaching the SiPM. A 28 V bias voltage was applied to the SiPM and its fast output was connected to a ZX6043-S+ 4GHz amplifier whose output was connected to a Keysight MSOV334V oscilloscope (33GHz, 80 GS/s). The captured 8b10b data was then post-processed in MATLAB®. In particular the signal was low-pass filtered and in some experiments decision feedback equalization (DFE) was applied to the signal to compensate for ISI. Finally, the bit error rate (BER) was calculated.

IV. Experimental Results

Data transmission experiments, over a distance of 30 cm, were performed at eight, approximately equally spaced , data rates from 500 Mbit/s up to maximum achievable 3.45 Gbits/s. Due to the finite width of SiPM output pulses and other transient effects, the system suffers from inter-symbol interference and therefore DFE was often employed before the BER was calculated. The irradiance from the transmitter was varied, using the polarizer, until a BER of 10^{-3} was achieved at each data rate. Finally, the irradiance at the SiPM receiver was measured by replacing the SiPM with an 818-SL calibrated photodiode.

The data rates with BERs of 10^{-3} at various irradiances are shown in Fig 4. The first conclusion from these results is that without equalization the maximum achievable data rate is

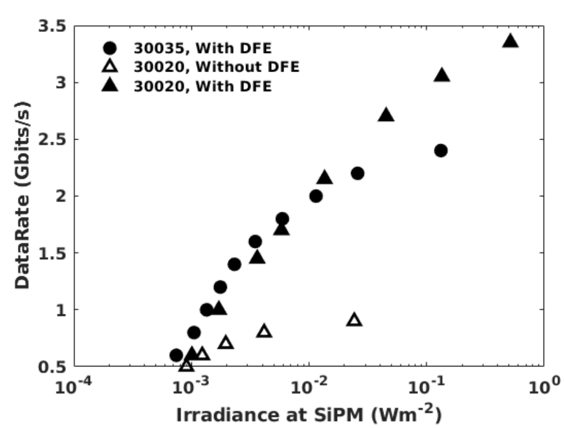

Fig. 4. The maximum achievable OOK data rate in 500 lux of ambient light for a white LED, as a function of average irradiance from the transmitter when DFE is used to achieve a BER of 10^{-3}.

approximately 1 Gbit/s. In addition, the results demonstrate that in a region where neither of the SiPMs are saturated, the 30035 requires a lower irradiance than the 30020 to achieve the same data rates. This is because the 30035 has a slightly better photon detection efficiency than the 30020. However, for data rates more than 2 Gbits/s, saturation begins to have an impact of the 30035's performance and the 30020 supports higher data rates at the same irradiance. At data rates above 2.5 Gbits/s saturation begins to affect the performance of the 30020.

The 30020 data rates between 1 Gbit/s and 2 Gbits/s suggest that the irradiance, and hence count rate, must increase by a factor of approximately 10 to increase the data rate by 1.5 Gbits/s. Since the maximum count rate of the 30020 is 4.1 times higher than the 30035 this observed trend suggests that the maximum possible data rate achievable by the 30020 should be 0.92 Gbit/s more than that achievable by the 30035. The similarity between this prediction and results in Fig 4 shows that the 30020 supports a higher maximum possible data rate because it has a higher maximum count rate.

The results in Fig. 4 were obtained when a filter was used to reject ambient light. However, the filter restricts the field of view of the receiver. The BER when the 30020 is used in the receiver has therefore been measured in 500 lux of ambient light and with an average irradiance from the transmitter of 500 mWm^{-2}. At each data rate experiments were performed with and without the optical filter. The results in Fig 5 show that under these conditions the optical filter has little effect on the performance of the receiver. This is because, to maintain a high bandwidth, the laser diodes modulation depth is limited. This limited modulation depth and the sensitivity of the SiPM to shorter wavelengths mean that the count rate from ambient light is much smaller than the count rate from the transmitter. Consequently, under these conditions removing the filter only reduces the data rate at which a BER of 10^{-3} can be achieved from 3.45 Gbits/s to 3.2 Gbits/s.

The results in Fig. 4 were obtained with the BER of 10^{-3}. However, the performance of VLC systems have previously been reported at BER of $2x10^{-3}$[6] and $3.8x10^{-3}$[7-9]. The results in Fig. 5 show that with a BER of $2x10^{-3}$ the data rates without and with the optical filter are 3.4 Gbits/s and 3.6 Gbits/s respectively. However, a more commonly used BER when VLC receiver performances are reported is $3.8x10^{-3}$[7-9]. If this BER is acceptable then the maximum possible data rates are 3.6 Gbits/s, without the filter, and 3.8 Gbits/s, with the filter. More importantly, the BER at which results are reported makes only a relatively small difference to the maximum achievable data rate.

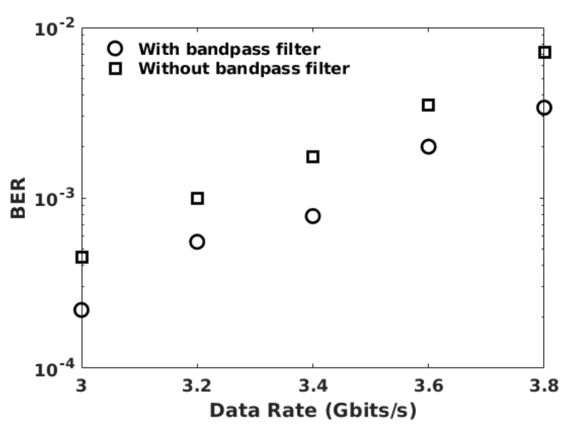

Fig. 5. The BER as a function of data rate when the irradiance from the 405 nm laser diode is $500mWm^{-2}$ in the presence of 500 lux of ambient white light both with and without a 405nm optical bandpass filter.

V. Conclusion

A relationship between the current needed to maintain the SiPM's bias voltage at different irradiances has been shown to agree with experimental data. In addition to clearly showing the impact of the saturation of the SiPMs response this relationship can be used to determine the power consumed by the SiPM.

Results have been presented which show that increasing the maximum count rate of a SiPM by a factor of 10 will increase the maximum achievable data rate by 1.5 Gbits/s. This observation explains why the higher maxumum count rate of the 30020 means that, at a BER of 10^{-3}, it can support data rates up to 3.45 Gbits/s. Further work is required to create SiPM receivers with higher maximum count rates so that they can support OOK data rates of more than 5 Gbits/s in 500 lux of ambient light. Their increased count rate will also make them more robust than other SiPMs to the high peak powers that occur when orthogonal frequency-division multiplexing (OFDM) is the preferred modulation scheme.

Acknowledgment

The authors thank Grahame Faulkner (Oxford University) for his support and guidance during this investigation.

References

[1] F. Zafar, M. Bakaul, and R. Parthiban, “Laser-diode-based visible light communication: Toward gigabit class communication,” IEEE Communications Magazine, vol. 55, no. 2, pp. 144–151, 2017.

[2] D. O'Brien, S. Rajbhandari, and H. Chun, “Transmitter and receiver technologies for optical wireless,” Philosophical Transactions of the Royal Society A, vol. 378, no. 2169, p. 20190182, 2020.

[3] Z. Ahmed, R. Singh, W. Ali, G. Faulkner, D. O'Brien and S. Collins, "A SiPM-Based VLC Receiver for Gigabit Communication Using OOK Modulation," in *IEEE Photonics Technology Letters*, vol. 32, no. 6, pp. 317-320, 15 March15, 2020

[4] Onsemi.com. 2020. *J-Series SiPM Sensors Datasheet*. [online] Available at: https://www.onsemi.com/pub/Collateral/MICROJ-SERIES-D.PDF, Accessed 10 March 2020.

[5] L. Zhang, D. Chitnis, H. Chun, S. Rajbhandari, G Faulkner, D. O'Brien and S. Colllins.., "A Comparison of APD- and SPAD-Based Receivers for Visible Light Communications," in Journal of Lightwave Technology, vol. 36, no. 12, pp. 2435-2442, 15 June15, 2018.

[6] H. Zimmermann, "APD and SPAD Receivers: Invited Paper," 2019 15th International Conference on Telecommunications (ConTEL), Graz, Austria, 2019, pp. 1-5.

[7] Yuanquan Wang, Yiguang Wang, Nan Chi, Jianjun Yu, and Huiliang Shang, "Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED," Opt. Express 21, 1203-1208 (2013)

[8] R. Bian, I. Tavakkolnia and H. Haas, "15.73 Gb/s Visible Light Communication With Off-the-Shelf LEDs," in Journal of Lightwave Technology, vol. 37, no. 10, pp. 2418-2424, 15 May15, 2019.

[9] Yoshida, K., Manousiadis, P.P., Bian, R. et al. 245 MHz bandwidth organic light-emitting diodes used in a gigabit optical wireless data link. Nat Commun 11, 1171 (2020).