Silicon photomultiplier receivers and future VLC systems

Wajahat Ali
Department of Engineering Science
University of Oxford
Oxford, UK
wajahat.ali@eng.ox.ac.uk

Grahame Faulkner
Department of Engineering Science
University of Oxford
Oxford, UK
grahame.faulkner@eng.ox.ac.uk

Zubair Ahmed
Department of Engineering Science
University of Oxford
Oxford, UK
zubair.ahmed@eng.ox.ac.uk

William Matthews
Department of Engineering Science
University of Oxford
Oxford, UK
william.matthews@univ.ox.ac.uk

Dominic O’Brien
Department of Engineering Science
University of Oxford
Oxford, UK
dominic.obrien@eng.ox.ac.uk

Steve Collins
Department of Engineering Science
University of Oxford
Oxford, UK
steve.collins@eng.ox.ac.uk

***Abstract*—The performance of a Silicon photomultiplier (SiPM) receiver when used with a 405 nm transmitter is discussed. A comparison of the irradiance available from a low-power transmitter that covers 20 m^2 and the performance of the SiPM shows that in an indoor application this combination of transmitter and receiver can support OOK data rates of 1 Gbps. A comparison of the performance of the SiPM and an OEIC highlights the benefits that arise from the relatively large area of the SiPMs. Finally, the potential impact of using SiPMs on future VLC systems is discussed.**

Keywords—Silicon photomultiplier (SiPM), Visible Light Communication (VLC).

I. INTRODUCTION

The capacity of a VLC channel depends upon both the bandwidth of the channel and the signal to noise ratio (SNR) at the receiver’s output. One approach to reducing the noise in the receiver is to place an APD in series with a quenching device and bias it above its breakdown voltage. The resulting single photon avalanche diode (SPAD) can be used to detect single photons. However, a SPAD needs a few nanoseconds to recover after each detected photon. The problems associated with this recovery time means that arrays of SPADs [1,2] known as Silicon photomultipliers (SiPMs), are preferred in receivers. Recently, it has been demonstrated that for data rates less than 1 Gbps a SiPM receiver is 9 dB more sensitive than any other receiver [3].

In this paper the advantages of transmitting data to a SiPMs using 405 nm light will be explained. Since this choice raises the possibility that the transmitter might be a blue-light hazard the power available from a down-link transmitter in the lowest possible blue-light risk category is calculated for the first time. Given the advantages of restricting the transmitter power it is then argued that for free space applications comparisons between receivers should be based upon the irradiance, rather than power, which a receiver requires to support a particular data rate. Results are then presented that show that their sensitivity and large area means that SiPMs can operate at irradiances that are two orders of magnitude smaller than a state-of-the-art optoelectronic integrated circuit containing an avalanche photodiode. The first comparison of the irradiance available from a safe, low power 405 nm transmitter and results from experiments with an SiPM receiver show that they could be used to create a link that covers 20 m^2 and supports an OOK data rate of 1 Gbps.

TABLE. 1: Key SiPM Parameters [4]

Parameter		
Name	30035	30020
Area (mm2)	9.42	9.42
No. of SPADs	5676	14410
SPAD diameter (µm)	35	35
Fill Factor (%)	75	62
Recharge Time (ns)	45	15
PDE (405 nm)	0.47	0.35
Dark Count Rate (MHz)	1.35	1.25
Output Pulse Width (ns)	1.5	1.4
Max. Count Rate (Gcps)	46.4	353

The paper is organised as follows. The operation and characteristics of SiPMs are discussed in section II. The potential impact of ambient light on the performance of SiPMs is then discussed in section III. The choice of 405 nm as the wavelength for transmitting data is explained in Section IV. Since this choice raises possible concerns about a blue-light hazard the power available from a safe, exempt, transmitter is calculated in this section. The experimental equipment used to test SiPMs as receivers and the results of experiments are described in sections V and VI. Section VII contains a comparison of the performance of the SiPM and an OEIC as receivers. Finally section VIII is a discussion of the possible impact for future VLC systems and section IX contains concluding remarks.

II. SIPM CHARACTERISTICS

Arrays of SPADs, known as silicon photomultipliers (SiPMs) can now be purchased from vendors, including Hamamatsu, Ketek and On-Semiconductor. In all SiPMs a detected photon creates an output pulse with a finite duration. When the duration of these pulses is comparable to, or longer than, the symbol time they will cause inter-symbol interference (ISI). This means that an important consideration when selecting a SiPM for use in a VLC receiver is the duration of its output pulses. On-Semiconductor manufacture SiPMs with an output which is capacitively coupled to the

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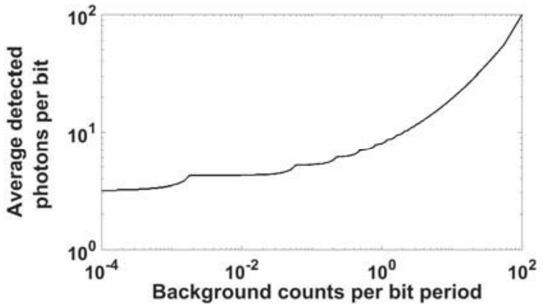

Fig. 1: The average required number of detected photons per bit required to achieve a target BER of 10^3 using OOK modulation as function of detected background photons per bit

anode within each SPAD which is discharged whenever a photon is detected. For the J series SiPMs, whose parameters are listed in Table 1 the full-width at half maximum of the pulses from this fast output is 1.5 ns [4]. This means that ISI is expected to start to occur when the OOK data rate is approximately 500 Mbps.

Another important non-ideal behaviour of SiPMs is that once an individual SPAD detects a photon the resulting self-sustained avalanche process has to be quenched by reducing the bias across the SPAD. This bias voltage then needs a finite time to recharge so that the SPAD is ready to detect another photon. This recharge time leads to a maximum count rate [5]

$$CR_{max}=N_{SPADs}/\tau.e \qquad (1)$$

where N_{SPADs} is the number of SPADs, is the dead-time and e is 2.71. The results in Table 1 show that with its larger number of SPADs and faster recovery time the 30020 has a significantly higher count rate than the 30035. This suggests that despite its lower PDE the 30020 will be able to support a higher data rate than the 30035.

III. IMPACT OF AMBIENT LIGHT

The advantage of SiPMs is that they can detect individual photons. This means that the number of photons needed to achieve the required bit error rate (BER) should be determined by Poisson or shot noise. Consequently, for an OOK signal the achievable BER should be given by:

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

where n_s and n_b are number of detected signal and background photons per symbol time respectively and th is the threshold used to determine if a bit is a zero or a one.

Fig. 1 shows the results obtained when (2) is used to calculate the average number of detected transmitted photons per symbol time required to achieve a BER of 10^3 for a range of detected background photons per symbol time. The results show that the required number of detected photons reaches a minimum when the number of detected background photons per symbol time is less that 10^{-4}.

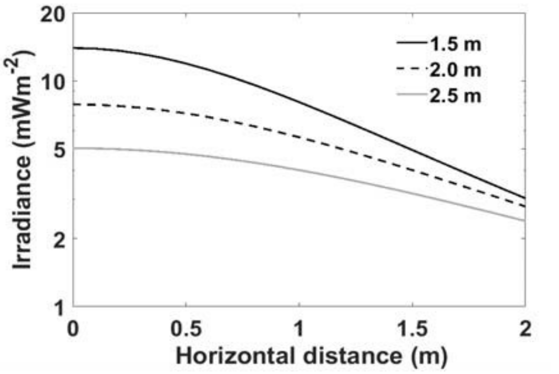

Fig. 2: The irradiance from a low power exempt 405 nm 65.8 mW transmitter at various horizontal distances and three different vertical distances from the transmitter and the receiver.

The minimum number of background photons in a symbol time is set by the dark count rate of the SiPM in Table 1. At a data rate of 500 Mbps, the minimum number of background counts per symbol is 2.7×10^{-3}. The results in Fig. 1 show that this will create a relative small power penalty.

IV. WAVELENGTH SELECTION

The low dark count rate of the SiPMs means that when they are operating in ambient light the VLC system should be designed to restrict the additional power penalty caused by any ambient light reaching the SiPM. This means using an optical filter in front of the SiPM and transmitting data at a wavelength at which there is less ambient light. The spectrum of ambient light produced by a white LED typically consists of a peak at 450 nm from a blue LED together with a peak between 500 nm and 600 nm from one or more phosphors. The amount of ambient light reaching the receiver can therefore be reduced by operating at wavelengths shorter than 450 nm or longer than 600 nm.

The SiPMs produced by On-Semiconductor have a photon detection efficiency of more than 45% at wavelengths between 400 nm and 450 nm but less than 20% at wavelengths longer than 600 nm. This characteristic of these devices means that the preference is operation at wavelengths shorter than 450 nm. The reduction in the amount of artificial ambient light at shorter wavelengths and the availability of a wide range of different transmitters then makes 405 nm a promising choice of transmitter wavelength.

A potential concern that can arise when transmitting data using 405 nm light is that it may create a blue light hazard. If the transmitter is an LED the relevant safety standard is the standard that is applied to LEDs used to illuminate spaces [6]. Alternatively, the transmitter may be a laser diode in which case the relevant safety standard is the one that is relevant to lasers [7]. Both of these standards have been consulted and the maximum powers available from the safest category of light source have been calculated for a 405 nm transmitter. If the transmitter light diverges from the transmitter with a half angle 45° the maximum power available under the LED standard is 329 mW. However, in this calculation the power at 405 nm is reduced by a factor of 5. In contrast, in the laser standard this risk is calculated without any reduction in the power at 405 nm. Following this more conservative approach the maximum allowable power is reduced by a factor of 5 to 65.8 mW. This difference creates a choice when determining the risk group of a 405 nm transmitter. However, using a maximum power of 65.8 mW would allow the use of LED or laser diode transmitters and is more power efficient.

For a Lambertian source with a power P the irradiance I at a distance d and an angle is

$$I=\left(\frac{P}{d^2}\right)\frac{m+1}{2\pi}\cos^m(\Phi) \qquad (3)$$

where $m=\ln(2)/\ln(\cos\Phi_{1/2})$ and $\Phi_{1/2}$ is the transmitter half angle at which the power is half the maximum power [8]. Figure 2 shows the irradiance from a 65.8 mW transmitter, when m=2 and $\Phi_{1/2}$ [illegible] was a function of the horizontal distance between the transmitter and a receiver for three vertical distances. The dimensions in Fig. 2 were chosen to represent a 3 m high room [9] and the calculations included effect of the projected area of the receiver. If the transmitters in the ceiling are 2.5 m apart [9] then to ensure coverage the maximum horizontal distance that each transmitter has to cover is 1.7 m. The results in Fig. 2 show that the minimum irradiance at this horizontal distance is 2.8 mWm^{-2}.

Taking into account the area and PDE of the SiPM this corresponds to 23 detected photons per bit at an OOK data rate of 1 Gbps. The results in Fig. 1 show that even in the presence of a significant number of background counts per bit data rates of 1 Gbps should be possible with a low power, exempt 405 nm transmitter.

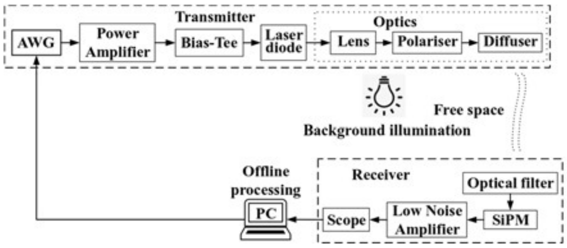

Fig. 3: System block diagram describes the experimental setup used to evaluate the performance of the selected SiPM.

V. EXPERIMENT SET-UP

A schematic diagram of the experimental setup used to determine the irradiance required at the SiPM to support different OOK data rates is shown in Fig. 3. In this set-up a 10 GHz Tektronix Arbitrary Waveform Generator (AWG) generated a pseudorandom binary sequence (PRBS). A Mini-Circuits ZFL-1000H+ amplifier then amplified the AWG output before it was combined with a DC bias voltage by a Mini-Circuits Bias-Tee (ZFBT-4R2GW+). This signal was then applied to a L405P20 laser diode that has an output wavelength of 405 nm. The last part of the transmitter was a polariser that could be used to vary the irradiance falling on the SiPM. In addition to the light from the laser diode the SiPM was also illuminated by a warm white LED that provided 500 lux to the surface of the SiPM.

The receiver section of the experiment consisted of a Thorlabs FB405-10 optical bandpass filter, with a central wavelength of 405 nm and a FWHM of 10 nm, which rejected most of the ambient light from the white LED falling on the SiPM. The SiPM was mounted on an evaluation board manufactured by On-Semiconductor. The fast output from the SiPM was connected to a ZFL-1000LN+ amplifier which amplified the output pulses from the SiPM before they were captured by a Keysight MSOV334A 33GHz, 80 GSps oscilloscope.

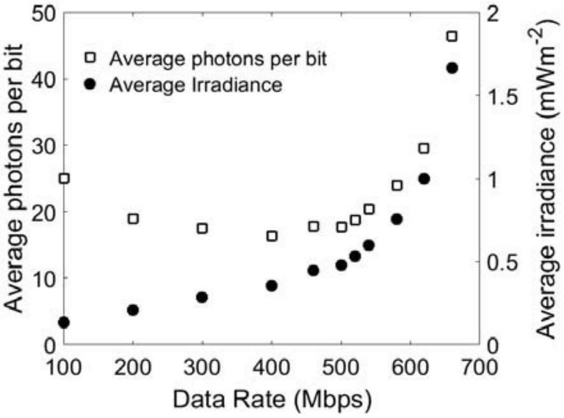

Fig. 4: Data Rate as a function of average irradiance for a 30035 SiPM with a 405 nm filter under 500 lux of ambient light. The experimental results are presented as both the average number of photons per bit and the irradiance.

VI. EXPERIMENTAL RESULTS

With the experimental setup described in section IV experiments were performed at several OOK data rates. At each of these data rates the polariser in front of the laser diode was used to vary the optical power falling on the SiPM until a BER of 10^{-3} was obtained. The SiPM was then removed and the optical power falling on the SiPM was measured using a calibrated photodiode and converted to an average irradiance falling on the SiPM.

The average photons per bit and average irradiance required to support different OOK data rate with a 10^{-3} BER without equalisation are shown in Fig. 4. The results in this figure show that as the data rate increases the number of photons per bit initially decreases before increasing again for data rates higher than 400 Mbps. A comparison with the estimated photons per bit calculated using (2) shows that the initial decrease in the photons per bit occurs because the number of background photons per bit reduces as the data rate increases. However, at data rates of 400 Mbps and higher the pulse width of the SiPM becomes comparable to the symbol time and causes ISI. Once ISI occurs the required number of photons per bit increases rapidly.

Fig. 4 also shows the average irradiance required to support different OOK data rates. For data rates less than 400 Mbps there is a linear relationship between the OOK data rate and the average irradiance falling on the SiPM, in particular

$$OOK_{Gbps}=1.4\times I - 0.082 \qquad (4)$$

where OOK_{Gbps} is the OOK data rate in Gigabits per second and I is the average irradiance in milliWatts per square metre.

For data rates higher than 400 Mbps the relationship between the average irradiance required to support a particular data rate becomes a non-linear function of data rate. This occurs when the bit time (2.5 ns) becomes comparable with the width of the output pulses.

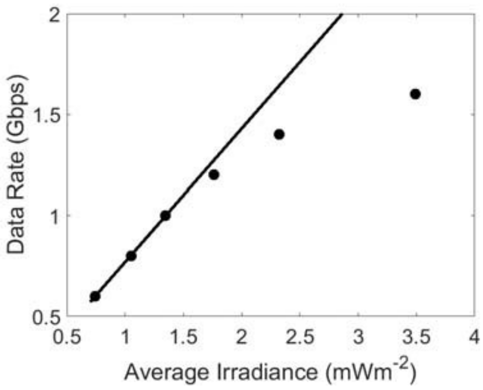

Fig. 5: Data Rate as a function of irradiance for a 30035 SiPM with a 405 nm filter under 500 lux of ambient light when DFE has been applied. The experimental results are dots and the line is a linear fit to the first three data points.

The impact of ISI has been reduced using decision feedback equalisation (DFE). The OOK data rate at which a BER of 10^{-3} was achieved with DFE at various average irradiances at the SiPM is shown in Fig 5. Also shown in Fig. 5 is a straight line approximation to the first three data points represented by the equation

$$OOK_{Gbps}=0.66\times I + 0.11 \qquad (5)$$

where again OOK_{Gbps} is the OOK data rate in Gigabits per second and I is the average irradiance in milliWatts per square metre. This linear relationship shows that when DFE is applied an average irradiance of 0.83 mWm $^{-2}$ is required to support a data rate of 600 Mpbs. In contrast, without DFE a data point in Fig 4 shows that an average irradiance of 1.66 mWm^{-2} was required to support the same data rate. This comparison confirms that the non-linear relationship between data rate and average irradiance in Fig. 4 is caused by ISI.

The linear relationship (5) is accurate at average irradiances less than 1.5 mWm^{-2}, which corresponds to a data rate of 1.1 Gbps. However, at higher irradiances the finite recovery time of the SPADs within the SiPM begins to have an effect and the effective photon detection efficiency of the SiPM is reduced and the data rate becomes a non-linear function of average irradiance

The data in Fig. 2 shows that the minimum irradiance available when exempt 405 nm transmitters are spaced 2.5 m apart is 2.8 mWm^{-2}. When the extinction ratio of the transmitter is 100% this corresponds to an average irradiance of 1.4 mWm^{-2}. Equation (5) shows that this corresponds to a data rate of 1 Gbps.

VII. COMPARISON WITH OTHER RECEIVERS

The results in Fig. 5 can be used to compare the performance of this SiPM to the performance of other receivers. Comparisons of the receivers have previously been based upon their sensitivity, which is the power required to achieve a particular data rate and bit error rate [10]. A state of the art optoelectronic integrated circuit (OEIC) that incorporated an APD achieved 1 Gbps at a BER of 10 $^{-3}$ with a power of -40 dBm [11]. The linear relationship (5) shows that this data rate and BER can be achieved at 1.35 mWm $^{-2}$, which corresponds to a power of -49 dBm. The SiPM is therefore more sensitive than the OEIC at this BER and data rate.

TABLE. 2: Comparison of two receivers when operating at a BER of 10^{-3} and an OOK data rate of 1Gbps.

Receiver	**Sensitivity (dBm)**	**Irradiance (mWm^{-2})**
OEIC	-40	800.0
SiPM	-49	1.35

Sensitivity is the appropriate measure of performance for a receiver at the end of an optical fibre. However, in a free space VLC system the aim is to cover an area with the lowest possible power. Consequently for these systems the irradiance required to support a particular data rate is the important parameter. The APD in the OEIC had a diameter of 400 µm and hence to achieve 1 Gbps at a BER of 10^{-3} this OEIC requires an irradiance of 800 mWm^{-2}. This is more than two orders of magnitude larger than the irradiance required by the SiPM to support the same data rate and BER. This comparison demonstrates that it is both their sensitivity and larger area that mean that SiPMs can operate at irradiances that are orders of magnitude lower than the irradiances required by other state of the art receivers.

VIII. IMPLICATIONS FOR FUTURE VLC SYSTEMS

The decision to minimise the impact of ambient light on an SiPM receiver by transmitting data using 405 nm light raises possible concerns about a resulting blue-light hazard. However, the resulting reduction in the impact of ambient light and the ability of the SiPMs to detect photons means that at this wavelength an SiPM receiver can support data rates of up 1 Gbps with irradiances of less than 1.5 mWm $^{-2}$. Rather than creating a blue-light hazard the choice to transmit data to a SiPM receiver using 405 nm enables links to be created with transmitters in the lowest possible risk category covering 20 m^2.

The safety categorisation of the transmitter will be reassuring to system installers and users. However, a more important consequence of the low irradiance required by the SiPM is that it creates the potential to use small low power LEDs as transmitters. An example of the wide range of small LEDs which could be used to create transmitters is the VLMU3100. These inexpensive LEDs have a peak wavelength of 405 nm, an output power of 6.8 mW. Several of these LEDs could be used to cover 20 m^2.

Another situation in which the low irradiances required by the SiPMs may be important is when the transmitter is embedded within a battery powered system. For example, the results in Fig. 2 shows that reducing the transmitters power to the 6.8 mW whilst retaining a 45° half angle field-of-view would result in irradiances of more than 0.28 mWm^{-2} at a receiver in the ceiling. Equation (4) then shows that the corresponding average irradiance, 0.14 mWm^{-2}, can support data rates of 100 Mbps without the need for equalisation. Furthermore, a VLMU3100 which can supply this amount of power is available in a 3.2 mm x 2.8 mm x 1.9 mm package which can be easily integrated into the thinnest smartphone.

IX. CONCLUSIONS

A combination of the photon detection efficiency of SiPMs and the spectra of artificial ambient light lead to the conclusion that a SiPM receiver should be used with a transmitter operating at 405 nm.

Since this choice raises the possibility that the transmitter might be a blue-light hazard the maximum power allowed in the lowest possible risk group has been calculated using the LED standard. The desire to create a power efficient system and the existence of a maximum safe power limit lead to the conclusion that comparisons between receivers should be based upon the irradiance that a receiver requires to support the desired data rate.

Results have been presented which showed that at a BER of 10^{-3} and a data rate of 1 Gbps the SiPM is 9 dB more sensitive than a state of the art OEIC that incorporates an APD. However, the large area of the SiPM means that the irradiance that the SiPM requires is more than two orders of magnitude lower than the irradiance required by the APD.

The minimum irradiance available in an office scenario from a safe 405 nm transmitter and results of experiments with the SiPM have been compared. This comparison lead to the conclusion that a safe, low power 405 nm transmitter and a SiPM receiver can be used to create a link in an office that supports OOK data rates of 1 Gbps.

The experimental results also lead to the conclusion that if a SiPM is used in an up-link receiver then a small, low-power, inexpensive LEDs could be used as the transmitter. If the up-link transmitter covers an area of 20 m^{2} on the ceiling of an office it should be possible to support data rates of up to 100 Mbps.

Despite increasing the amount of ambient light reaching the receiver the results that have been presented suggest that using a 6 mm by 6 mm SiPM would increase the up-link data rate available when a small, low power LED is used as the transmitter. Further work will then be required to determine how many transmitters each up-link receiver may need to support and to create a receiver that supports this number of up-links efficiently without any degradation in up-link performance.

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