Visible light communication at 50 Mbit/s using a red LED and an SPAD receiver

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***Abstract*—Visible light communication (VLC) is demonstrated at 50 Mbit/s using a 4-SPAD array receiver and a resonant-cavity-LED transmitter in a line-of-sight optical link configuration up to 5 m of transmitting distance for a bit-error ratio below $2{\cdot}10^{-3}$. Background light up to 2000 lux can be tolerated.**

***Keywords*—Visible light communication; SPAD; integrated SPAD receiver;**

I. INTRODUCTION

Visible light communication or Li-Fi is an expanding area of optical wireless communications (OWC) which promises to fulfill high speed demands of an indoor communication network. VLC relies heavily on LED light sources due to their growing popularity for indoor lighting and low power consumption [1]. For optical wireless receivers PIN photodiode receivers are often used due to their relatively low operating voltages. The PIN photodiode is usually wire bonded or in some cases fully integrated with a transimpedance amplifier [2]. However the PIN photodiode receivers are limited by the input referred noise current of the electrical circuitry thus achieving rather poor sensitivities which limits their use in OWC to docking applications or requires an expensive optics to increase the collected optical power. As a solution to the sensitivity challenges the avalanche photodiode (APD) optical receivers which work at higher biasing voltages have been investigated with promising results in Gbps range [3,4,5]. The APD receiver benefit from the internal gain of the APD which improves the sensitivity up to 10 dB compared to their PIN counterparts. The APD multiplication gain does not amplify only the optical signal but unfortunately also the photocurrent noise and generates additional noise which finally limits the sensitivity.

In order to bridge the sensitivity gap to the quantum limit, receivers operating the APDs above their breakdown voltage in the so called Geiger mode were investigated. These receivers are referred as single-photon avalanche photodiode (SPAD) receivers and they require a quenching circuit to stop the self-sustaining avalanche effect in the Geiger mode by reducing the bias voltage across the APD to below the breakdown voltage once the photons have been detected. Unlike linear mode APD receivers (operated below breakdown) the SPAD receivers generate non-linear digital output. Until recent years not many SPAD based receivers were investigated for the purpose of communication due to their parasitic effects such as afterpulsing [6] and optical cross talk [7]. These parasitic effects limit the use of SPAD receivers for higher data rates, especially in the wireless optical scenario where the presence of an ambient light aggravates these effects and the SPAD receiver can easily come into saturation. A common approach in combating these unwanted effects is to use an array of SPADs.

In this paper we are going to present measurement results of the 4-SPAD array receiver described in [8] where it was used as a fiber receiver and the optical input was coupled via fiber and generated with a 635 nm laser source using an external modulator to achieve an extinction ratio above 100. Here we are testing the performance of the 4-SPAD array receiver in OWC scenario; we use a 650 nm RCLED source in a direct line-of-sight (LOS) wireless optical link configuration at 50 Mbit/s data rate at different transmitting distances. In a previous study we demonstrated a LOS communication over 2 m but using a highly collimated 635 nm laser source with very low output power (in the order of a few µW) [9]. Now we want to explore the high extinction ratio and high average output power (1.1 mW) of an LED source in order to achieve greater transmitting distances. Additionally, in difference to the 635 nm laser source [8] the LED source does not require a feedback control loop with monitoring photodiode for maintaining the high extinction ratio.

II. VLC SYSTEM DESIGN

A. Transmitter

For an optical source a resonant cavity light emitting diode (RCLED) was used that emits at a peak wavelength of 650 nm and has a spectral width of 20 nm (full width at half maximum, FWHM). For a forward voltage of 2 V the LED's forward current is specified to be 20 mA; optical rise and fall times at this forward current are both 2 ns (bandwidth ≈ 110 MHz) [10]. RCLED-based development board was used for driving the RCLED at 50 Mbit/s using a non return to zero (NRZ) binary stream generated by an Agilent 81134A bit pattern generator. The output optical power at this speed was 1.1 mW, while the

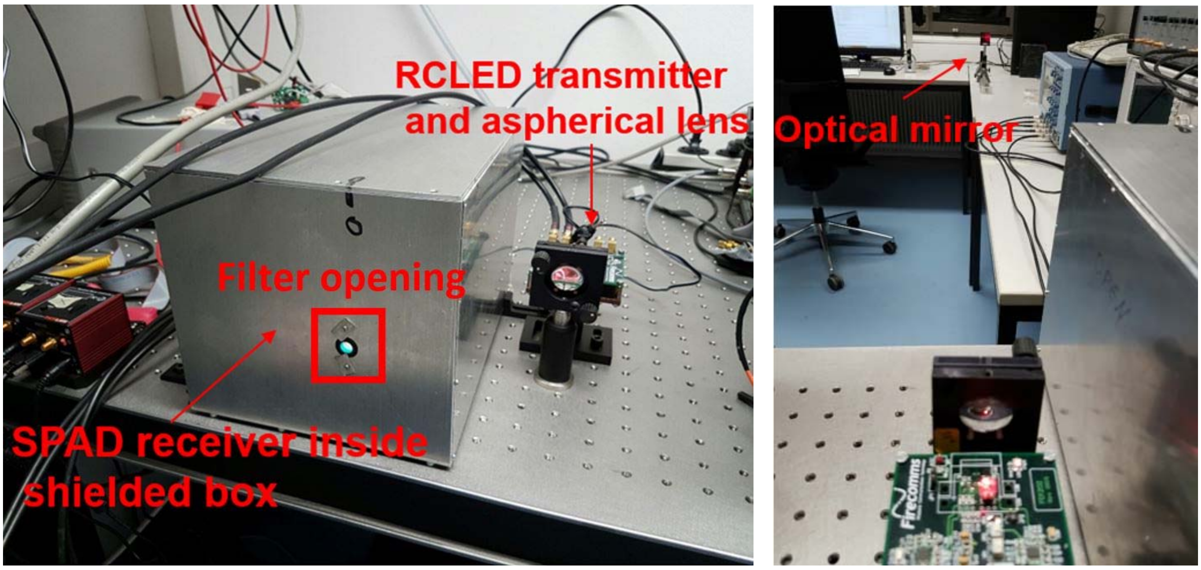

Fig. 1. VLC system setup: SPAD receiver inside the shielded box nect to RCLED transmiter with aspherical lens and optical mirror for reflecting the transmitter's beam

measured forward current flowing through the device was 30 mA. At 30 mA forward LED current the maximum NRZ data rate specified in the datasheet is 250 Mbit/s. The resonant cavity LED had an integrated optical lens resulting in a small emission aperture NA = 0.35. Additional focusing aspherical lens with a focal length $f_c = 25.4$ mm was placed in front of the LED source, at distances longer than the focal length, so that the full beam divergence was not larger than 0.038 rad.

B. *SPAD Receiver*

The details of the SPAD receiver's operation and implementation are described in [8] where it was used for optical fiber communication. The test chip was developed in 0.35 µm PIN-photodiode CMOS technology. The integrated SPAD receiver is a 4-channel receiver since the 200 µm photodiode diameter is divided into four quadrants with a fill factor of 53%; each channel has its own quenching circuit. The dead time of the quenching control circuit is 9 ns, and it is the limiting factor for the achievable speed, although the active quenching circuit quenches the SPAD completely within less than 1 ns after detection of an avalanche event at a low threshold of 100 mV. The outputs of four channels were buffered on chip and fed into a 4-channel digital sampling oscilloscope where they could be stored for later digital processing in Matlab. The postprocessing was done in Matlab since our bit pattern receivers for BER measurements only operate at higher data rates and also because the receiver has 4 outputs which, in this implementation, need to be combined off chip. This combination and the derivation of a bit stream out of the 4 output channels can be done in Matlab with two different approaches: the analog and the digital approach, see [8]. In this experiment only the digital approach is used since it is more suitable for future integration that generates the bit stream directly on chip.

In the digital approach, each of the four active quencher outputs of the SPAD receiver was converted to digital in Matlab processing by latching at the positive edge. The four latched outputs were summed in Matlab, and the decision threshold of the number of triggered SPADs necessary for a logical "1" could be changed easily in Matlab (threshold of 1, 2, 3, or all 4 out of 4 SPADs). The BER was calculated in Matlab by shifting the obtained latched bit stream (synchronization) on the time axis and comparing it to the reference data stream used for laser modulation and counting the bit errors. More details on the postprocessing method can be found in [8].

The maximum reverse voltage across each SPAD is the sum of the substrate voltage V_{sub} connected to anode and positive 6.6 V bias voltage V_{plus} which can be connected to the SPAD's cathode. The breakdown voltage of the SPAD is 25.8 V. Similarly like in [8] in order to vary the excess bias voltage (voltage above breakdown voltage of the photodiode) the substrate voltage was varied in 0.5 V steps during the following experiments in order to find the optimum working point for the SPAD receiver.

For the purpose of this measurement the receiver was placed inside a shielded box that allowed only a small opening for the incoming signal. A 650 nm bandpass filter from Edmund optics was placed inside the opening to block the unwanted ambient light. Except for the bandpass filter the SPAD receiver did not use any other optics.

III. VLC EXPERIMENTS

For determining the optical link performance, we modulated the transmitter beam with a NRZ pseudorandom binary sequence (PRBS) with the length of 2^7-1 at a data rate of 50 Mbit/s using a bit pattern generator. For crosschecking the results the length of the PRBS sequence was chosen to be

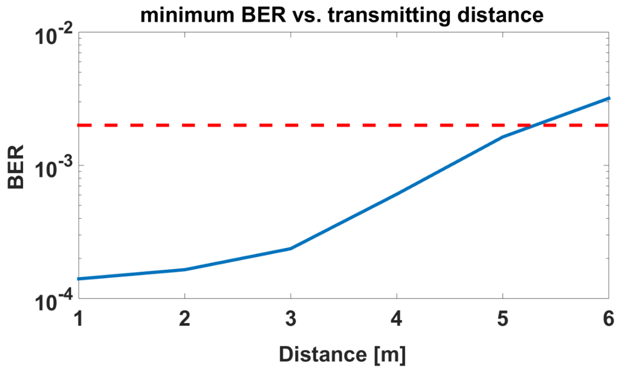

Fig. 2. BER versus distance at 50 Mbit/s at optimum substrate voltages

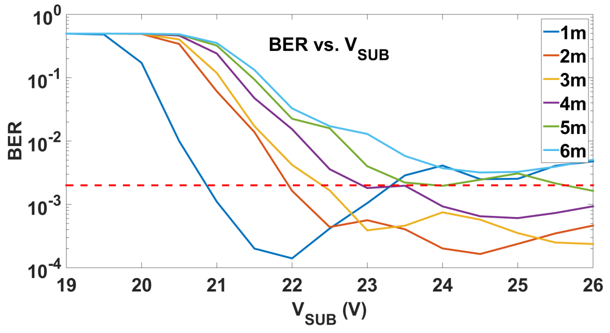

Fig. 3. BER versus substrate voltage at different transmitting distances

the same as in [8], where it was limited by AC coupling of the laser source. The receiver and transmitter were mounted inside our lab facilities operating under normal lighting conditions (500 lux). In order to save space for the LOS link, an optical mirror was used to reflect the beam from the transmitter onto the receiver. The system setup can be seen in Fig 1.

A. BER vs. transmitting distance

In order to verify the performance at different transmitting distances the position of the mirror was varied from 0.5 m to 3 m resulting in the total link distances from 1 m to 6 m. For each distance the substrate voltage was varied from -19 V to -26 V. Fig. 2 shows the dependence of the BER for an optimum set of postprocessing parameters (synchronization delay, substrate voltage and decision threshold i.e. number of triggered SPADs for logical ‘1’) at each transmitting distance. As the distances increase, due to the geometrical path loss the average power at the receiver side decreases. The red line represents the BER limit of $2 \cdot 10^{-3}$ below which forward error correction can be performed [11]. The maximum transmitting distance for this BER limit is 5 m, and the optimum substrate voltage was –26 V. At this distance the photodiode current originating only from the optical signal was 3.09 nA. This value was measured without ambient light and at the low substrate voltage of -2 V at which the low field responsivity of the photodiode is 0.49 A/W [12]. This photodiode current value corresponds to an optical power of 6.3 nW or -52 dBm, which is very close to the measured sensitivity of -51.2 dBm

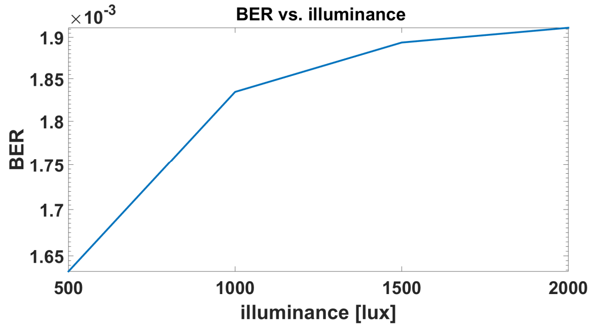

Fig. 4. BER versus illuminance at 5 m transmitting distance at 50 Mbit/s

[8] when a 635 nm laser source was used and an optical fiber was coupled to the SPAD array. The small difference compared to experiment with fiber coupled laser source, even in the presence of the ambient light can be explained with a steep slope of the bandpass filter that blocked most of the unwanted spectrum but also due to the fact that LED sources offer a higher extinction ratio than lasers.

Fig. 3. shows the dependence of the BER on the substrate voltage Vsub of the SPAD at 50 Mbit/s at different optical link distances i.e. different optical powers. At the distance of 1 m the received optical power is quite high, and the BER shows low value at Vsub = -22 V which corresponds to relatively low excess bias voltage of 2.8 V (the SPAD’s total reverse bias voltage is Vsub + Vplus: 22.0 V+6.6 V). The measured low field (Vsub = -2 V) signal current at this distance is 95.6 nA which for a responsivity of 0.49 A/W corresponds to 195.1 nW optical power. At such high optical power levels many charge carriers are generated during SPAD event which can be trapped and give rise to afterpulsing probabilities. For this reason at 1 m the BER value starts to rise very fast for higher Vsub voltages i.e. higher excess bias voltages since they too lead to higher afterpulsing probability and optical cross talk. As the link distances increase, less optical power is received and the the BER curves are shifting upwards, and there is no such strong dependence with excess bias voltage. At higher transmitting distances minimum BERs are achieved for substrate bias voltages above 24 V i. e. excess bias voltages above 4.8 V. This is an expected behavior since at the low incident optical powers we want to increase the photon detection efficiency (PDP) by means of increasing the excess bias voltage. Additionally, as the distance increases the optimum decision threshold (number of SPADs for logical ‘1’) decreases since the probability that all four SPADs will be triggered during the ‘1’ bit is small at low signal optical powers.

B. Background light immunity

The influence of background light was investigated with an adjustable *Euromex* cold-light source which uses a 67627 HLX halogen lamp from OSRAM with aluminum coating and emission spectrum that ranges from near ultraviolet up to infrared wavelengths. The adjustable light source was placed in front of the receiver when the reflecting mirror was fixed to 2.5 m so that the transmitting distance was near the maximum of 5 m (BER < $2\cdot10^{-3}$). The illuminance of the adjustable light source was measured with a luxmeter (Testo 545) in the range from 500 lux (standard reading light conditions) up to 2000 lux. The measured values were taken in front of the interference filter, when the external light source was pointed towards it. The results of the influence of different background light illuminance levels can be seen in Fig 4, the interference filter allows for the SPAD receiver to operate properly up to 2000 lux when the BER approaches the $2\cdot10^{-3}$ limit. Here as the level of background light increases also the probability of false '1' detection increases. Illuminance levels above 2000 lux would cause too many bit errors, however typical indoor lighting conditions are below this value.

IV. CONCLUSION

In this paper we demonstrated an optical system for line-of-sight communication where a 4-SPAD array receiver was used. The transmitting distance was up to 5 m for a BER limit of $2\cdot10^{-3}$ which is to the best of the author's knowledge the longest transmitting distance with a SPAD based receiver at speed of 50 Mbit/s. The receiver could operate at this distance even with high background illuminance levels up to 2000 lux. This result is especially important given the parasitic effects inherent in SPAD detection mechanism. These effects are the main reason why there are not many case studies reported with SPAD based optical communication receivers although they promise to reduce the needed optical power for a given BER. Some of recently published results with SPAD receivers used in wireless optical communication are [13] and [14]. In [13] an array of 60 SPADs was used for indoor optical communication under 800 lux of background light. A data rate of 200 Mbit/s was transmitted via 650 nm collimated RC LED source, however the needed optical power or the transmitting distance for achieving the $2\cdot10^{-3}$ BER was not reported. VLC at 60 Mbit/s at 2 m of transmitting distance was reported in [14]. The data rate was divided into three different channels using the RGB LED diode, each of the channels required an array of 128 × 32 SPADs. For an individual channel operating under 1040 lux of ambient light at a data rate of 20 Mbit/s an optical sensitivity of -49.4 dBm was achieved with BER = $0.91\cdot10^{-3}$. In this paper at 50 Mbit/s the optical power of -52 dBm is sufficient for a BER of $2\cdot10^{-3}$ even up to 2000 lux of ambient light using an array of only 4 SPADs. By using the bandpass filter we have shown that SPAD receivers can be used in practical ambient lighting conditions for data rates far in the Mbit range where they offer very high sensitivity. These results show promising prospects for SPAD based optical wireless communication and hope to drive the research direction towards further speed and sensitivity improvements.

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