Non-Line-of-Sight Indoor Optical Wireless Communication Using a Silicon Photomultiplier (SiPM)

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Abstract: *This paper investigates the use of a SiPM sensor for OWC transmission with NLOS channels. The results suggest that while SiPM's bandwidth limitations are not a major factor, irradiance affects transmission data rates, supporting data rates of up to 125 Mbps.*

Keywords: *Optical wireless communication (OWC), Non-line-of-sight (NLOS), Silicon photomultiplier (SiPM), Photon counting*

I. Introduction

Optical wireless communication (OWC) is an emerging technology that offers several advantages over traditional radio frequency (RF) communication, including high-speed data transmission, low power consumption, and enhanced security [1], [2]. These benefits make OWC a promising complement to existing RF infrastructure, especially in various indoor environments, such as homes, offices, and industrial settings. However, OWC systems primarily rely on line-of-sight (LOS) communication [3], which limits their applicability in many real-world indoor scenarios where obstacles like furniture, walls, and people can obstruct the signal. In such cases, non-line-of-sight (NLOS) communication plays a crucial role in ensuring reliable connectivity. Since NLOS optical signals are typically weak, transmission performance highly depends on the sensitivity of the photodetector. The most sensitive photodetectors are those capable of accurately counting the number of photons arriving at the sensor within individual symbol periods. An advanced type of photon-counting sensor, the silicon photomultiplier (SiPM), which consists of a large array of single-photon avalanche diodes (SPADs), has demonstrated promising performance in detecting weak optical signals with extremely low intensities. This makes it a strong candidate for supporting NLOS communication in indoor OWC systems [4], [5].

In this paper, we construct an OWC transmission setup with NLOS channels and investigate the use of a commercially available SiPM sensor, manufactured by Onsemi, to detect light scattered from a wall in an indoor lab environment. First, we measure and discuss two important factors affecting the use of SiPMs in optical communication: (1) the SiPM nonlinearity, caused by the dead time/recovery period of individual SPADs or microcells, and (2) the SiPM bandwidth, directly related to the width of the electrical pulse generated by each detected photon. Next, we measure the OWC transmission performance with a NLOS channel at different data rates and irradiance levels with optical orthogonal frequency division multiplexing (OFDM) modulation. The results show that, although the scattered light from the wall is weak, the SiPM can still support a transmission data rate of 125 Mbps, which is sufficient for many practical applications. Additionally, we demonstrate that, in the case of detecting diffused light, the SiPM's bandwidth is not the limiting factor for the transmission data rate, but rather the irradiance of the light. Transmission data rates increase significantly as the irradiance increases, although the SiPM becomes nonlinear at higher irradiance levels.

II. SiPM nonlinearity and bandwidth

When a SiPM is used in OWC systems, two key parameters that significantly impact transmission performance are the nonlinearity and bandwidth of the SiPM. When a photon strikes a SiPM microcell, it initiates an avalanche process, followed by a passive quenching phase. This cycle generates an electrical pulse, enabling the detection of the corresponding photon. However, during both the avalanche and quenching stages, the SiPM requires recharging to restore its photon detection efficiency (PDE). Photons that arrive during this recharge period can not be detected or detected with reduced PDE, introducing a nonlinear effect [6]. As a result, the average photon counting rate, and consequently, the average bias current of the SiPM become nonlinearly related to the irradiance incident on the device. Fig. 1 (a) shows both the theoretical and measured results for the relationship between the irradiance incident on the SiPM and its bias current. It can be seen that when the SiPM irradiance is below 10 $\mathrm{mW/m^2}$ or the bias current is below 10 mA, the SiPM operates approximately linearly. However, when the irradiance exceeds 10 $\mathrm{mW/m^2}$, the SiPM exhibits nonlinear behavior and eventually saturates at a bias current of approximately 35 mA. In OWC, this nonlinearity can cause severe signal distortion when the transmission data rate and/or the received optical power are high.

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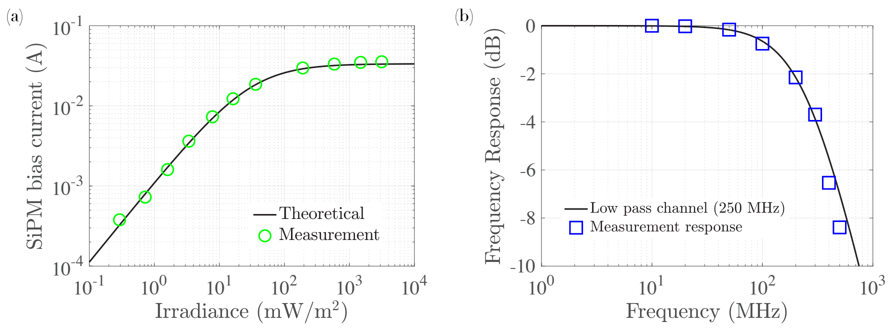

Fig. 1. (a) SiPM bias current versus irradiance on the SiPM 30020, (b) frequency response of the SiPM 30020.

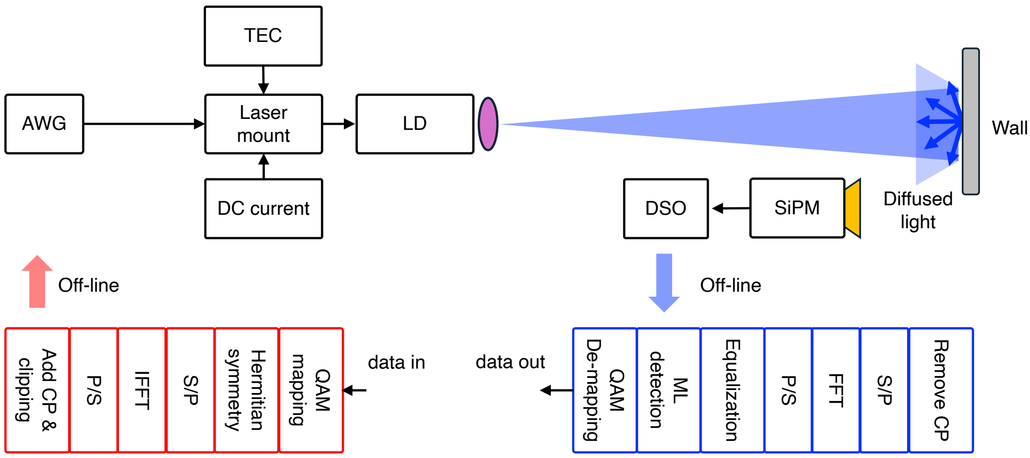

Fig. 2. Block diagram of the NLOS OWC transmission setup.

The second parameter that should be considered when selecting a SiPM is its bandwidth. As explained, a detected photon can generate an electrical pulse. Moreover, when the transmission data rate is high, the generated electrical pulses associated with different signal symbols can overlap, resulting in forms of ISI and therefore a bandwidth-limited channel. Fortunately, the SiPM manufactured by ON-Semi has a capacitively coupled fast output, which uses additional capacitors to reduce the pulse width, thereby achieving a high modulation bandwidth. Fig. 1 (f) shows the measured frequency response of the SiPM 30020 considered in this work. It can be seen that its 3 dB bandwidth is 250 MHz. Additionally, the measured result matches the theoretical plot obtained based on the frequency response a single-pole low-pass filter [7].

III. OWC TRANSMISSION SETUP

Figure 2 shows the block diagram of the OWC transmission system. In this system, we used OFDM as the modulation method. The OFDM signal was generated offline using MATLAB. Since we employed intensity modulation and direct detection (IM/DD), the generated baseband OFDM signal needed to be real. To ensure this, the quadrature amplitude modulation (QAM) symbols input to the inverse fast Fourier transform (IFFT) were constrained to have Hermitian symmetry. Additionally, the top and bottom of the OFDM signal were clipped at 10 dB to suppress high signal peaks, thereby increasing the modulation depth, while keeping clipping distortion negligible. Next, the generated OFDM signal sequence was uploaded to an arbitrary waveform generator (AWG, Siglent, SDG6052X). The output of the AWG was sent to a commercially available laser mount (Thorlabs, LDM56/M), which includes an internal bias-T to combine the OFDM signal with a DC current supplied by a current driver (Thorlabs, LDC200C) to drive a 450 nm TO Can laser diode (Thorlabs, L450G2). The temperature of the laser diode was controlled via a TEC controller (Thorlabs, TED200C). In this study, the laser bias current was set to 40 mA, which is a middle value between the threshold current and the maximum current. The peak-to-peak voltage of the AWG was also fixed at 3.5 Vpp, ensuring a high modulation depth.

At the receiver side, a SiPM (ON-semi, 30020) was used to detect the received light intensity signal. The SiPM 30020 was mounted on a commercially available PCB evaluation board with a bias voltage of 28 V. The PCB board contains both a standard output and a capacitively coupled fast output. In this work, we used the fast output, and its signal was captured via a digital sampling oscilloscope (Rigol, DHO4404). Then, the captured signal was processed offline to recover the transmitted bits. This process involved transforming the received signal into the frequency domain using a fast Fourier transform (FFT) and applying single-tap equalizers to each subcarrier. Following equalization, the received QAM symbols were mapped to binary bits using the maximum likelihood (ML) detection principle. Finally, we compared the transmitted and received bit sequences to calculate the bit error rates (BERs) for evaluating the performance of the transmission link.

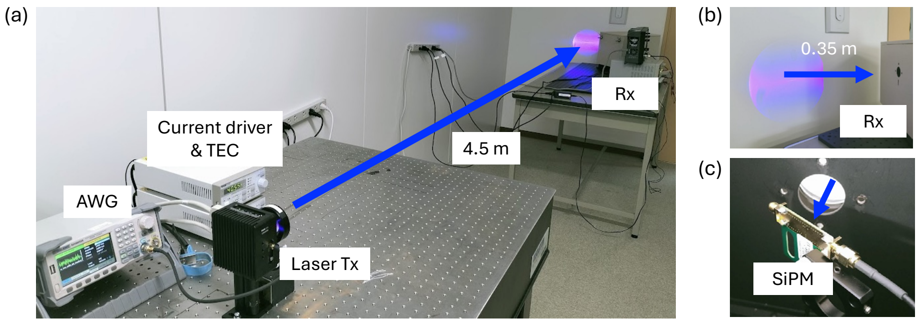

Fig. 3. A photograph of the OWC transmission experiment.

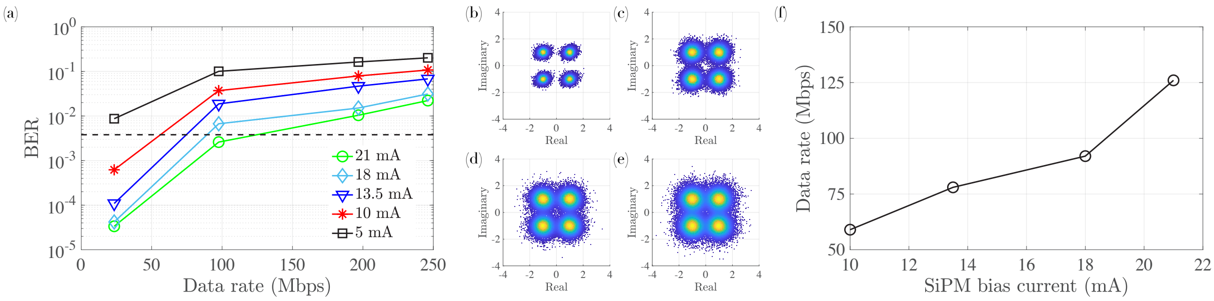

Fig. 4. (a) Measured BERs at different transmission data rates, (b)–(e) received QAM constellations at four different transmission data rates,25 Mbps, 100 Mbps, 200 Mbps, 250 Mbps, when the SiPM bias current is 21 mA. (f) achievable transmission data rates associated with different SiPM bias currents.

Figure 3 shows a photograph of the transmission setup, along with a close-up of the receiver. As shown in Fig. 3(a), the light emitted from the laser diode passes through a lens, creating a circular light spot on the wall, which is 4.5 m away from the transmitter. The circular light spot has a diameter of 30 cm, forming a diffused light source. As shown in Fig. 3(b)-(c), the SiPM was placed inside a box to detect the light diffused from the wall. The box was used to reduce the amount of ambient light reaching the SiPM. To ensure that the field of view (FOV) of the receiver was not restricted, no lens was placed in front of the SiPM. The distance between the center of the light spot and the SiPM was approximately 35 cm. Additionally, during the data transmission measurements, the lights in the lab were switched off. However, some ambient light still entered through the windows, resulting in an ambient illumination level of 15 lux in the room. Under these conditions, when the signal light was off, the bias current of the SiPM was 1.2 mA due to the ambient light.

IV. OWC TRANSMISSION RESULTS

Figure 4 (a) shows the measured BERs at different transmission data rates under various irradiance levels. In this measurement, different irradiance levels were achieved by placing neutral density (ND) filters in front of the laser diodes. ND filters with different transmittances were considered, including 10%, 28%, 40%, and 70%, resulting in different SiPM bias currents of 5 mA, 10 mA, 13.5 mA, and 18 mA, respectively. When no ND filter was used, the SiPM bias current was 21 mA. It can be seen from the BER results shown in Fig.4(a) and the received QAM symbols shown in Fig.4(b)–(e) that, as the data rate increases, the BER also increases. Additionally, for the considered irradiance levels, higher irradiance is associated with lower BER. Considering the FEC limit of 3.8×10^{-3}, the achievable data rates under different irradiance levels, and therefore different SiPM bias currents, are plotted in Fig. 4(a). The results show that the achievable data rates can reach up to 125 Mbps from diffuse light, which is sufficient to support many practical applications. Furthermore, given that the 3 dB bandwidth of the SiPM is 250 MHz, it can be concluded that bandwidth is not the limiting factor for the data rate, as the observed data rates are in the range of several tens of Mbps. The results shown in Fig. 4(b) indicate that the data rate can significantly increase as the irradiance increases. Since the SiPM becomes non-linear when the bias current exceeds 10 mA, the higher data rates achieved in these experiments were obtained when the SiPM became non-linear.

V. CONCLUSION

In this paper, we demonstrate the use of a commercially available SiPM to enable NLOS transmission in an indoor environment. Despite the weak intensity of diffused light, our results show that a data rate of 125 Mbps is achievable. These findings underscore the strong potential of SiPMs for NLOS OWC applications.

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