Up-to 292-Mbps Deep-UV Communication over a Diffuse-Line-of-Sight Link Based on Silicon Photo Multiplier Array

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Abstract *Towards a Gbps-class outdoor mobile optical wireless communication (OWC), we experimentally investigate an up-to 292-Mbps diffuse-line-of-sight OWC in the solar-blind band based on an AlGaN-LED and a Silicon photo multiplier array under a typical indoor illumination condition.*

Introduction

Short-reach optical wireless communication (OWC) systems based on high-speed light-emitting diode (LED) is an important building block of 5G and beyond 5G small-cell networks [1]. Recently, high-speed OWC systems in the solar-blind band (λ< 300 nm) based on advanced deep-ultraviolet (DUV) LEDs have been demonstrated as an outdoor OWC solution[2-6]. In [2], a 71-Mbps near-solar-blind LED-based OWC at 294 nm was demonstrated over an 8-cm diffuse line-of-sight (LoS) channel. A 2-Gbps transmission over a 1.5-m direct LoS channel was achieved by using an AlGaN-based LED in the 280-nm band[3]. A 1-Gbps OWC over a 30-cm LoS channel by using III-nitride micro-LEDs at 262 nm was shown[4]. Very recently, a 2.4-Gbps/1.09 OWC at 279 nm over a 1-m LoS/5-m diffuse LoS link was demonstrated[5, 6]. In addition, a carrier localisation structure in AlGaN-based LEDs, which might enable these high-speed demonstrations, was reported[7, 8].

Those works mainly focused on the modulation speed of the advanced DUV LED devices, and few works have been reported on the design and the implementation of Gbps-class *solar-blind receivers*. In the previous demonstrations, submillimetre-scale Silicon photodetectors (SiPDs) were employed at the receiver in order to fully exploit the bandwidth of the DUV-LEDs. Since SiPD has sensitivity between 190-1100 nm, most of the demonstrations were conducted in dark rooms. Some optical solar-blind filters are necessary in practice. However, the transmit power of DUV-OWC should be below the DUV exposure limit, that is 10^5 to 10^6 times smaller than the solar irradiance level[9]. In addition, the photosensitivity of SiPD in the DUV band is less than half of that in the near IR band[10]. Consequently, the previous experimental results in dark rooms cannot be simply extended to the outdoor scenario only by introducing an off-the-shelf solar-blind filter. In [11], the authors characterized their DUV-OWC system in an outdoor daylighting condition by introducing a solar-blind bandpass filter; even with a directed LoS configuration, the achievable bit rate was around 1 Gbps, which was a half of that in a dark room. The implementation of the high-speed solar blind receiver becomes more challenging in the outdoor mobile OWC over a diffuse/nondirected LoS channel based on wide-angle transceivers.

In this work, towards a Gbps-class outdoor mobile DUV-OWC, we experimentally investigate a solar-blind receiver based on a Silicon photo multiplier (SiPM) array. SiPM array, also known as multi-pixel photon counter (MPPC), is a fast,

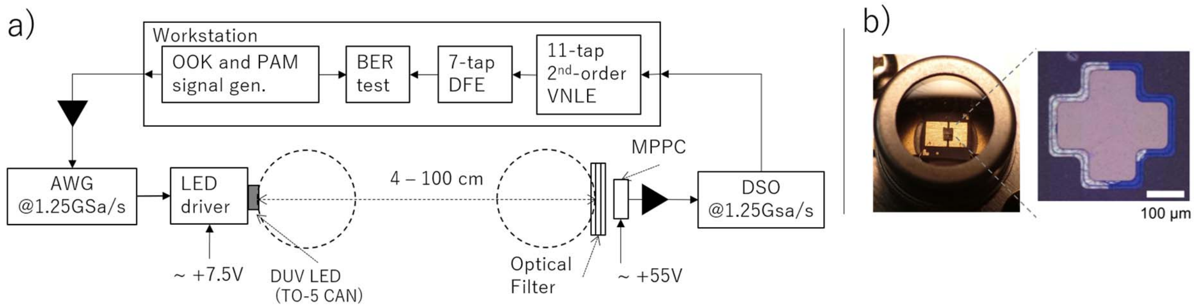

Fig. 1: a) Experimental setup for solar-blind OWC over diffuse-LoS link and b) photo image of AlGaN-LED.

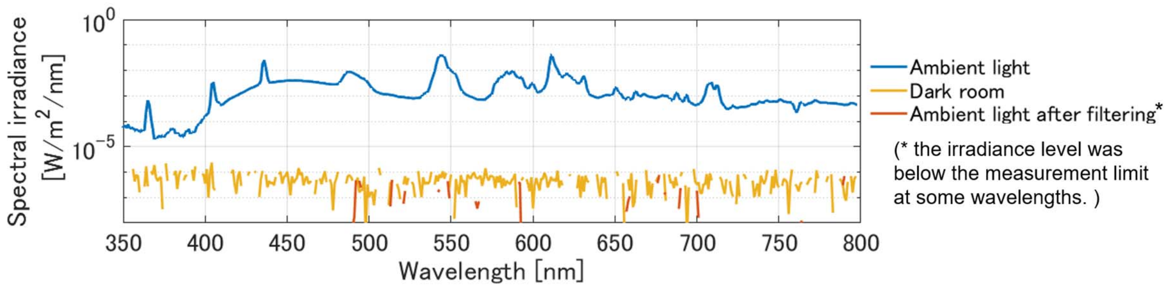

Fig. 2: Spectral irradiance from 350 nm to 800 nm before and after filtering

compact, and potentially cost-effective photon counting device comprised of arrays of Geiger mode avalanche photodiodes[12]. In the past decade, MPPC has been received increasing attention in many areas, such as high-energy physics and medical imaging. Recently, MPPC has also been addressed as an attractive receiver solution for the visible light communication (VLC) [13,14]. Although few experimental results have been reported on the high-speed MPPC-based OWC so far, an advanced MPPC device is expected to realize 1-Gbps-class transmission with 4-orders of magnitude higher sensitivity than PIN-PD-based receivers[13]. In this work, we further address MPPC as a receiver solution in DUV-OWC and demonstrate a >100-Mbps OWC using a MPPC-based solar-blind receiver experimentally for the first time. Actually, typical MPPC devices have > 10^5 gain and easily saturate under practical lighting (or solar irradiation) levels. The use of MPPC in the solar-blind band eases the problem of the saturation. A solar-blind OWC system with an AlGaN-LED-based transmitter in the 280-nm band and a MPPC receiver with a high-rejection-ratio (OD4) solar-blind filter achieved an up-to 292-Mbps transmission over a diffuse-LoS link with the wide-angle transceivers under a typical indoor illumination condition.

Experimental Results

Fig .1a) shows the experimental setup. At the transmitter, a 1.25-GSa/s arbitrary waveform generator (AWG, Keysight M8190A) generated OOK (on-off-keying) or PAM-4 (pulse amplitude modulation) RF signals at 62.5 to 312.5 Mbaud. After amplification, the 2-V_{pp} RF signal was launched into an AlGaN-based LED. The LED was the same device as in [7,11]; its peak wavelength was 285 nm and the 3-dB bandwidth was 153 MHz. With + 7.5 V bias voltage, the optical output power from the LED was around 3 mW. The LED was packaged in TO5-CAN without any focus lenses as shown in Fig. 2b). After passing through an up-to 100 cm diffuse-LoS channel, the ambient light in the visible and infrared bands was rejected by a multilayer solar-blind filter. The filter output was detected by a non-cooled MPPC (Hamamatsu MPPC13360CS series). Concentration lenses were not employed at the receiver. The MPPC output was amplified by a current amplifier with 40-MHz 3-dB bandwidth and then sampled at 1.25 GSa/s by a digital sampling oscilloscope (DSO) (Tectronix DSA72004C). DSPs for equalization and demodulation were done in an off-line manner. To mitigate the bandwidth limitation and the nonlinearity of MPPC[12], we employed a 11-tap 2nd-order adaptive Volterra nonlinear equalizer (VNLE) based on a recursive least squares (RLS) algorithm followed by a 5-tap decision feed-back equalizer (DFE) as shown in the inset of Fig. 1 a).

Fig. 2 shows the spectral irradiance from 350 to 800 nm before and after filtering. The experiment was carried out under the general indoor illumination level required for a workspace, i.e., ~500 lux. The optical filter has a rejection level of 0.001 % (OD4) and the central wavelength of its passband was 280 nm with 30-% transmittance. As shown in Fig. 2, after filtering, the ambient noise from the room lights and the sun was suppressed well below the illumination level of the dark room (with the room lights turned off and the blackout curtains closed) over the entire visible band. In fact, the irradiance level after filtering was below the measurement limit at most wavelengths.

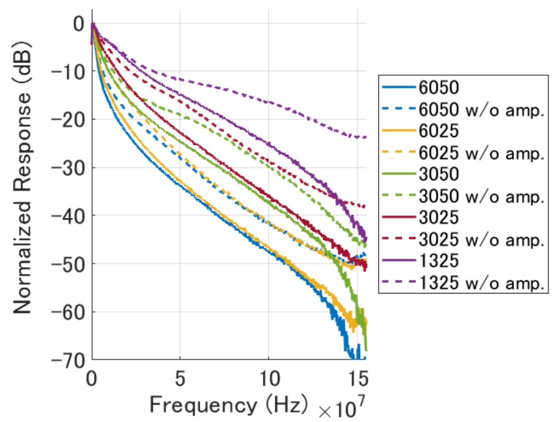

Fig.3: Frequency response (periodogram) of solar-blind OWC channel including DUV-LED and MPPC responses.

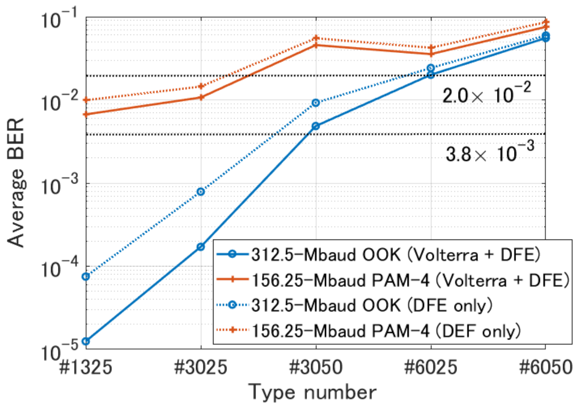

Fig.4: BER for different MPPC types.

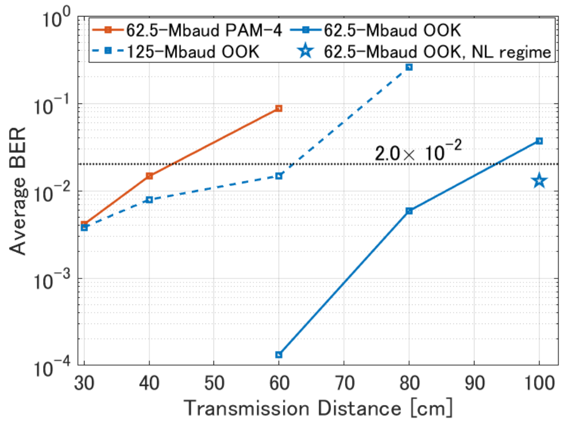

Fig.5: BER versus transmission distance (#6050).

Next, we investigated the end-to-end bandwidth of the OWC link. Here MPPCs with different sizes and pixel pitches, i.e., Hamamatsu MPPC13360CS-1325, 3025, 3050, 6025, and 6050, were evaluated. (The last 4 digits, i.e., XXYY, indicates that the effective photosensitive area of the device size is X.X ×X.X mm and the pixel pitch is YY μm.) Fig. 3 is the frequency response of the entire OWC link including the responses of the DUV-LED and MPPC operated at its break down voltage. The response was estimated based on the least square criterion in the digital domain by using a 312.5-Mbaud PAM-4 pilot sequence. Note that each spectrum is normalized based on its peak value. The transmission distance was chosen to level the output currents from these MPPC devices, e.g., 4.5cm and 32 cm for #1325 and #6050, respectively. As in Fig. 3, the 3-dB bandwidth of the entire OWC channel was < 10MHz in each case. Since the LED has the 3-dB bandwidth of >150MHz[7,11], the bandwidth limitation was caused by the MPPCs. However, the very high SNR of the solar-blind OWC channel allowed to use the MPPC devices beyond their 3-dB bandwidth. It is worth mentioning that the bandwidth shown in Fig. 3 might not be consistent with the data sheet or the previous work[12]; Fig. 3 shows the response of the MPPCs for random short pulse sequence with limited modulation index.

Fig. 4 represents the averaged bit-error rate (BER) performance of the OWC system with different MPPCs for 312.5-Mbaud OOK and 156.25-Mbaud PAM-4 transmissions. The current amplifier was not used in this case. As shown in Fig. 4, the 20%-overhead Forward Error Correction (FEC) limit, i.e., 2.0×10^{-2}, was achieved for 312.5-Mbaud OOK transmission with #6025. The effective bit rate was 260 Mbps over a 23 cm diffuse-LoS link. With #1325 and #3025, the BER was well below the 7%-FEC limit, i.e., 3.8×10^{-3} and the effective bitrate of 292 Mbps was achieved. In case with #1325 and #3025, a 260-Mbps PAM-4 transmission was also possible.

Finally, Fig. 5 shows the BER performance versus transmission distance with the most sensitive device, i.e., #6050, which has a gain of 1.7×10^{6}. The current amplifier was used. As shown in the figure, the effective bit rate of 104 Mbps was possible over a 60-cm diffuse-LoS link in 125-Mbaud OOK transmission. The same data rate was achieved with 62.5-Mbaud PAM-4 up to 40-cm. In case with 62.5-Mbaud OOK, the reach was extended to 80 cm. Furthermore, in case with the OOK format, it was possible to extend the reach by driving the LED in nonlinear regime, i.e., ~3.5-$V_{p\text{-}p}$ driving voltage with 6.2-V bias voltage. In the nonlinear driving condition, a 52-Mbps transmission over a 100-cm diffuse-LoS link was achieved (the pentagram in Fig. 5). Note that any focus or concentration lenses were not employed in the experiment.

Conclusions

Towards a Gbps-class outdoor mobile OWC, an up-to 292-Mbps solar-blind OWC system based on an AlGaN-based DUV-LED and a MPPC was demonstrated experimentally. Owing to the high sensitivity of the MPPC receiver and the low ambient light in the solar-blind band, >100-Mbps transmission was achieved over an up-to 60-cm diffuse-LoS link without focus or concentration lenses under a typical indoor illuminaion condition.

Acknowledgements

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