Gbps-Class Solar-Blind WDM Optical Wireless Communication By (264, 274, 282)-nm Deep-UV LEDs and CsTe Photomultiplier Tube

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Abstract: A Gbps-class wavelength-division multiplexing transmission within the solar-blind band was demonstrated for the first time with (264, 274, 282)-nm AlGaN-based LEDs and a CsTe photomultiplier-tube over a 2-m weakly-collimated free-space link in standard indoor illumination.

1. Introduction

High-speed optical wireless communication (OWC) is a viable solution to the predicted capacity crunch in RF communications [1]. Recently, Gbps-class OWC systems in the solar-blind band (λ< 300 nm) based upon deep-ultraviolet (DUV) LED technologies have been demonstrated towards a high-speed OWC solution in outdoors [2-4]. A DUV-LED-based OWC with data rate beyond 1 Gbps was first demonstrated by utilizing an off-the-shelf AlGaN LED device with ~150-MHz bandwidth in 2018 [2]. In 2021, a record data rate of 4.6 Gbps was achieved by utilizing a micro DUV LED array with ~600-MHz optical bandwidth [4]. However, the previous works mainly focused on the modulation speed of the advanced DUV LED devices and employed a submillimeter-scale high-speed Silicon photodetector (SiPD), which has sensitivity between 190-1100 nm, at the receiver. Therefore, most of the demonstrations were carried out in a dark room, and the optical link was strictly collimated or focused for better coupling. A large beamforming and/or concentrator lens was often used. In [5], a wide field-of-view (FoV) solar-blind receiver based on a high-gain silicon photo multiplier (SiPM) array was introduced towards a practical outdoor OWC system. However, the data rate was restricted, e.g., ~100 Mbps over a 60-cm diffused line-of-sight (LoS) link, due to the path loss, the bandwidth of the SiPM array, and the excess loss due to the high-rejection-ratio solar-blind filter.

In this paper, we report an experimental demonstration of a DUV-LED-based wavelength-division multiplexing (WDM) OWC within the solar-blind band at a net data rate of 1 Gbps over a 2-m weakly collimated LoS link (the divergence angle of ~8 degrees) in a standard room illumination condition. To attain Gbit-class capacity while keeping wide FoV and solar-blindness of the transceivers, we employed AlGaN-LEDs with peak emission wavelengths of 264, 274, and 282 nm, and a high-speed solar-blind photomultiplier tube (PMT) with Cesium Telluride (CsTe) photocathode, which allowed us to remove the lossy solar-blind filters. In [6], a 10-Gbps WDM transmission using UV-LEDs was demonstrated. However, the wavelengths of the LEDs were 281, 316, and 373 nm and not fully inside the solar-blind band. The FoV and the solar-blindness of the receiver were not considered. To the authors' knowledge, this work is the first demonstration of a Gbps-class LED-based WDM transmission within the solar-blind band.

2. Experimental Setup

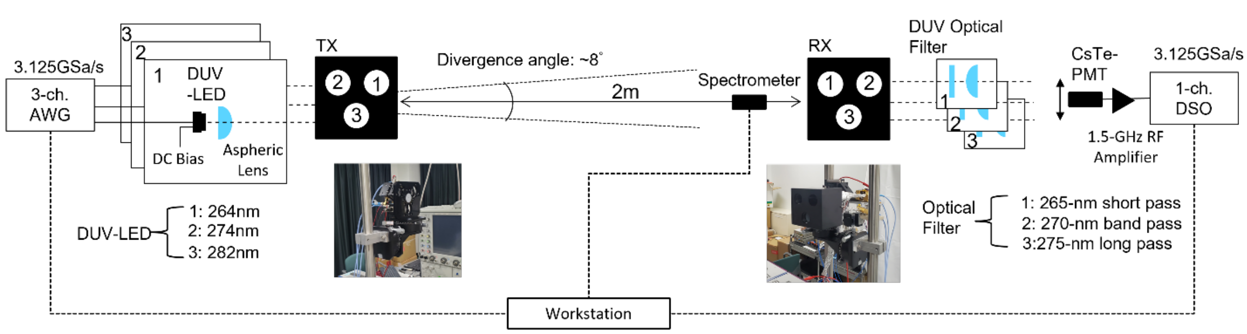

Fig. 1 Experimental setup for a Gbps-class solar-blind 3-channel WDM OWC with AlGaN DUV-LEDs and a CsTe-PMT.

Fig. 1 shows the experimental setup for a Gbps-class solar-blind WDM OWC system. The transmitter comprised of a 3-channel arbitrary waveform generator (AWG, Keysight M8190A) at 3.125-GSa/s, DUV LEDs, and aspheric lenses for beamforming. The DUV LEDs based on AlGaN grown on AlN/sapphire templates with vicinal off-angles (See [7] for more details). The DUV LEDs had the self-organized micro-LED structure and exhibited ~150-MHz 3-dB bandwidths. The peak wavelengths were 264, 274, and 282 nm; they were within the solar-blind spectrum range (typ. 200 to 300 nm). The output powers were around 3 mW with 5.7 to 6.2 V bias voltages. Each emitted light was weakly collimated by an aspheric lens (Thorlabs ASL2520) with a 25-mm aperture diameter. The LED modules were arranged in a triangle with a 6-cm pitch. The optical wireless channel was a 2-m indoor LoS link in a well-lit room. The diameter of each beam spot at the receiver was around 30 cm and the effective beam divergence angle was approximately 8 degrees. The three beam spots overlapped each other at the receiver. Fig. 2 (bottom) shows the spectral irradiance measured by a spectrometer in front of the receiver with and without room lighting. The peak power from each LED was set to be two or more orders of magnitude smaller than that of the fluorescent lamps in the room not to exceed the deep UV exposure limit. Note that, the spectral irradiance from the lamps in Fig. 2 was observed in a horizon direction. The actual irradiance on the worktable was two or more times higher than that in Fig. 2 (*i.e.*, 439 lux) and the illumination level was ~1,000 lux.

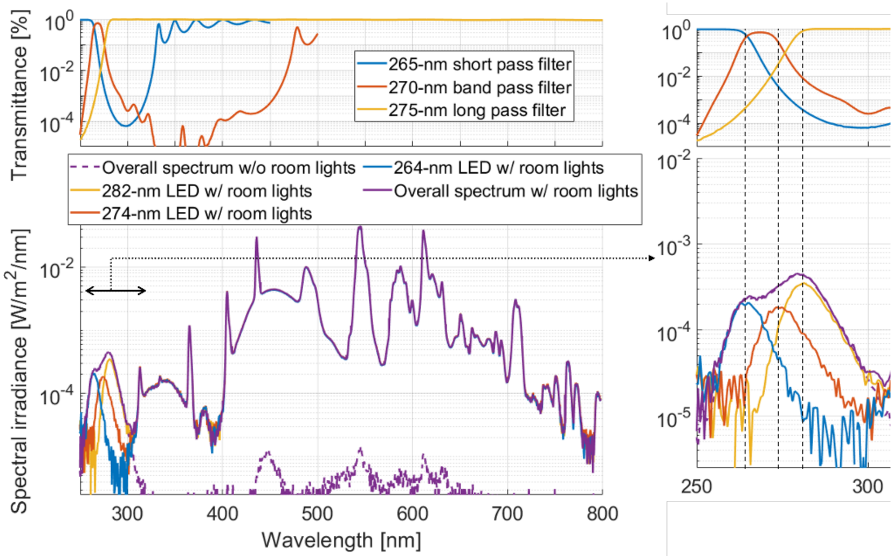

Fig. 2 Spectral irradiance and the transmittance of DUV WDM filters.

The receiver front-end comprised of DUV optical filters, optical concentrators, and a solar-blind PMT. The receiver had the same aperture size and placement as the transmitter. To de-multiplex the WDM channels, multilayer film optical filters (Asahi Spectra SUX, LUX, and LX series) were implemented. The transmittance of the filters is shown in Fig. 2 (top). A 265-nm shot-pass filter and a 275-nm long-pass filter were adopted for the shortest and the longest wavelength channels, respectively. Meanwhile, due to equipment limitation, a 270-nm bandpass filter was employed for the middle, 274-nm, channel. The mismatch caused an excess loss and inter-channel interference (ICI) to the channel. The concentrator lenses at the receiver were the same as those at the transmitter. The incident lights were then detected by a high-speed solar-blind PMT (Hamamatsu H10721-19) channel by channel. The PMT module was 14 x 22 x 50 mm large including a high-voltage power supply circuit. The build-in PMT device had a CsTe photocathode with a spectral response range from 160 nm to 320 nm, allowed it to block the illumination/solar spectrum without external solar-blind filters. The PMT had an effective area of 8 mm in diameter and a gain of 10^6 typically. Due to the large effective area, the FoV of the receiver was much wider than that of the transmitter.

The PMT output was then current-to-voltage converted by a 1.5-GHz amplifier (Hamamatsu C5594) and sampled at 3.125 GSa/s by a digital storage oscilloscope (DSO, Tectronix DSA72004C) for off-line processing. In the off-line DSP, a multiple-input single-output (MISO) 2nd-order diagonal Volterra decision feedback equalizer (VDFE) with 17 first-order taps was used for mitigating the bandwidth limitation and nonlinearity of the LED and the PMT in each WDM channel. In addition, we introduced a sequential interference cancellation (SIC) procedure to suppress the ICI: the WDM channels were equalized sequentially, and the equalizer output of the previous channel(s) was fed into the equalizer of the later channel(s). In the experiment, the channels were equalized in the order of 264 nm, 282-nm, and 274-nm. The equalizer tap weights were optimized based on

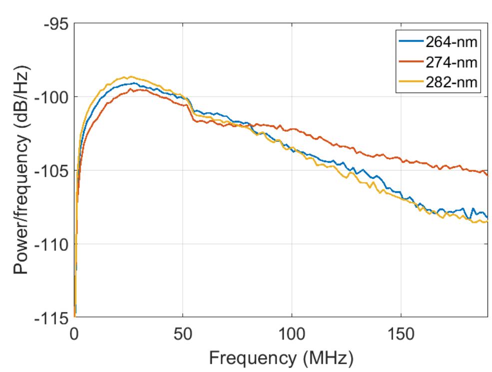

Fig. 3 Overall frequency response per WDM channel.

recursive least squares (RLS) by sending 10,000 three-level pulse amplitude modulation (PAM-3) pilot symbols.

3. Experimental Results

Figure 3 is the end-to-end frequency response of each WDM channel including the LED and PMT. The 3-dB bandwidths were 82 MHz, 102 MHz, and 73 MHz for the 264-nm, 274-nm, and 282-nm channels, respectively. The 3-dB bandwidths of the AlGaN LEDs were around 150-MHz. The overall response in Fig. 3 suggests that the bandwidth of the PMT module was almost comparable to those of the LEDs. It is worth mentioning that the low ambient noise level of OWC channels often allows a LED to be driven at the rate much higher than its 3-dB bandwidth as shown in [2-4]. However, in this experiment, the spurious noise from the electrical circuit in the PMT module limited the effective system bandwidth below 400 MHz.

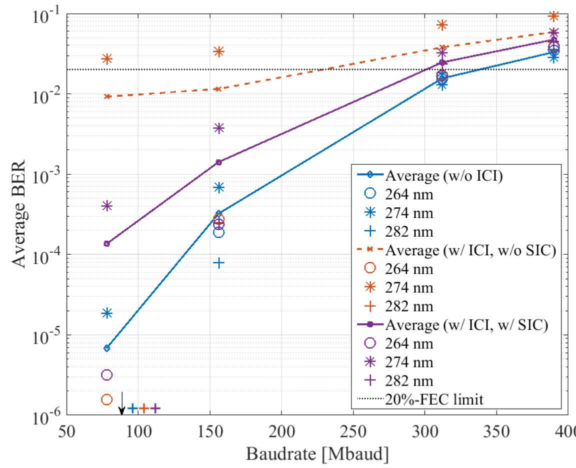

Fig. 4 Average and per-channel BER performances of 3-channel WDM PAM-3 transmission at 56 to 390 Mbaud.

Table 1 shows the bit error rate (BER) performance of the 274-nm channel, which suffered from the most severe ICI, in different illumination conditions. The modulation format was 390-Mbaud on-off keying (OOK) for all WDM channels. As in the table, the impact of the room lighting was negligible due to the solar-blind nature of the CsTe photocathode. Meanwhile, the ICI was the major performance limiting factor in the WDM case. The VDFE alone could not mitigate the ICI. The use of the SIC was a key to resolve the problem without increasing the cost and complexity for the DUV WDM filters.

Table 1 BER performance of the 274-nm channel with a 390-Mbaud OOK signal under different illumination conditions

# of WDM ch.	1	1	3	3	3	3
Room lights	off	on	off	On	off	on
Equalization	VDFE	VDFE	VDFE	VDFE	VDFE + SIC	VDFE + SIC
BER	6.37e-5	6.60e-5	1.10e-3	1.15e-3	3.23e-4	3.75e-4

Figure 4 shows the per-channel and averaged BER performance with different baudrates. The modulation format was PAM-3 for all channels. In the figure. ‘w/o ICI’ denotes the single channel transmission, and ‘w/ ICI’ is the 3-channel WDM transmission with and without the SIC. In the single channel transmission case, the BER limit for the 20%-overhead feedforward error correction (FEC), i.e., 2.0×10^{-2}, was achieved at up-to 340 Mbaud. The net data rate was estimated to be 1.27 Gbps. In the WDM case, the BER performance was significantly degraded due to the ICI on the 274-nm channel. Nevertheless, with the SIC, the average BER was below the FEC limit at up-to 300 Mbaud. The net data rate of 1.12 Gbps was achieved over a weakly-collimated 2-m free-space link in standard room lighting.

4. Conclusions

Towards a high-speed wide-FoV outdoor OWC system, a Gbps-class WDM transmission within the solar-blind band based on DUV LEDs was demonstrate for the first time. By (264, 274, 282)-nm AlGaN LED-based transmitters and a CsTe PMT-based receiver with a digital ICI cancellation technique, a solar-blind 3-channel WDM transmission with a net data rate of 1.12 Gbps was achieved over a 2-m weakly-collimated free-space link in a standard indoor illumination condition.

[1] H. Haas, “LiFi is a paradigm-shifting 5G technology,” Reviews in Physics, 3, 26 (2018).
[2] K. Kojima et al., “1.6-Gbps LED-based Ultraviolet Communication at 280 nm in Direct Sunlight,” in proc. ECOC (2018), Paper Th1B.3.
[3] O. Alkhazragi et al., “2.4-Gbps ultraviolet-C solar-blind communication based on probabilistically shaped DMT modulation,” in proc. OFC (2020)., Paper M3I.5.
[4] J. J. D. McKendry et al., "4 Gbps wireless optical communications up to 5 m using a UV-C micro-light-emitting diode array," in proc. IPC (2021), pp. 1–2.
[5] Y. Yoshida et al., “Up-to 292-Mbps Deep-UV Communication over a Diffuse-Line-of-Sight Link Based on Silicon Photo Multiplier Array," in proc. 2020 ECOC (2020), pp. 1–4.
[6] D. M. Maclure et al., "10 Gbps wavelength division multiplexing using UV-A, UV-B, and UV-C micro-LEDs," Photonics Res. 10(2), Res., 516-523 (2022).
[7] K. Kojima et al., "Self-organized micro-light-emitting diode structure for high-speed solar-blind optical wireless communications," Appl. Phys. Lett. 117(3), 031103 (2020).