Deep UV micro-LED arrays for optical communications

Xiangyu He,[1] Enyuan Xie,[1] Mohamed Sufyan Islim,[2] Ardimas Purwita,[2] Jonathan J. D. McKendry,[1] Erdan Gu,[1*] Harald Haas,[2] Martin D. Dawson[1]

[1]Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow, G1 1RD, UK
and
[2]Li–Fi R&D Centre, the University of Edinburgh, Institute for Digital Communications, King's Buildings, Mayfield Road, Edinburgh EH9 3JL, UK

Contact email: erdan.gu@strath.ac.uk

The Institute of Photonics is a member of the Scottish Universities Physics Alliance

Content

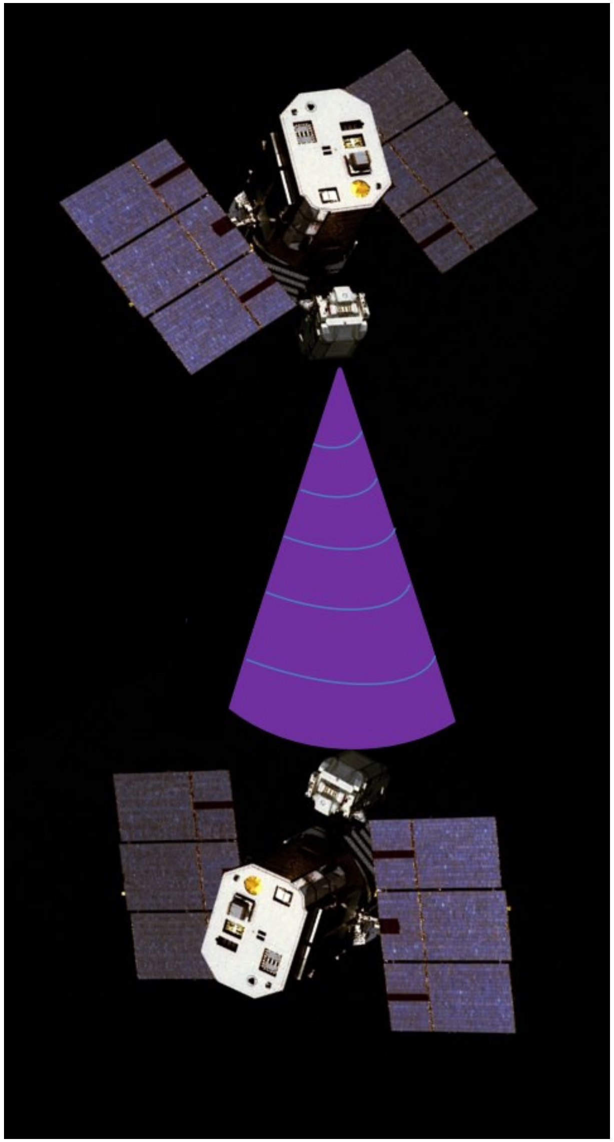
- Optical communications based on the UV band
- GaN-based μLED array
- Design, fabrication and performance of the UV-C μLED array
- Free-space optical communication based on the UV-C μLED array
- Summary and future work

Optical communication based on UV band

UV band based optical communication system

- **Advantages**
  - Ultraviolet radiation absorbed by the ozone layer in Earth's stratosphere[1]
    - High-security communication link in the upper atmosphere
    - Data transmission with low solar background noise for outdoor communication
  - Strongly scattering in the air caused by abundant molecules and aerosols
    - Non-line-of-sight short-range optical communication
- **Disadvantages**
  - Quite low data transmission rate compared with visible light communication
    - Low modulation speed of conventional deep UV light source

Need to develop new deep UV light sources with high data transmission performance



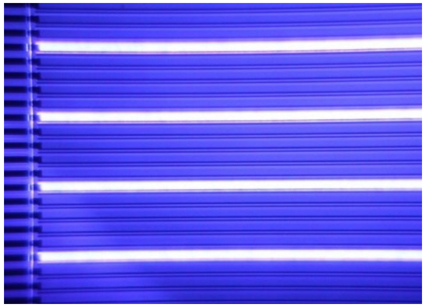
[1]*Zhengyuan, Xu., Ultraviolet Communications. Topics in Optical Communications, 2008.*

GaN-based μLED array

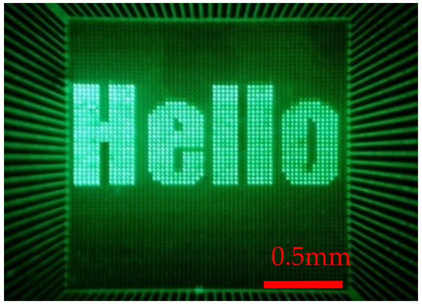
GaN-based micro-LED (μLED) array with element size less than 100 μm

- **Advantages**
  - Higher operation current & power densities
  - Excellent thermal properties
    - Heat dissipation through high surface-to-volume ratio
  - Higher modulation bandwidth over 600 MHz[1]
    - Small resistance-capacitance constant
    - High operation current density leading to the short carrier lifetime

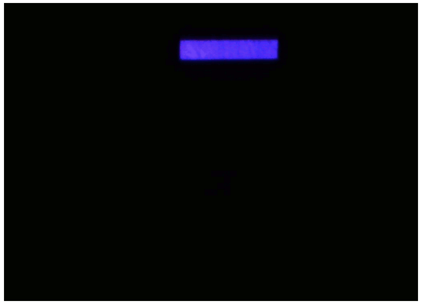
- **Excellent performance for visible light communications[2]:**
  - Over 7 Gb/s OFDM visible light communication achieved by using a single μLED



Micro-stripes



Matrix-addressable



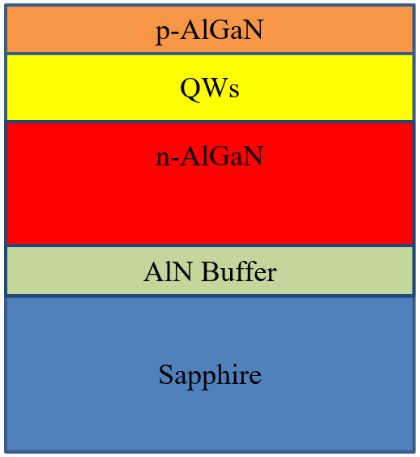
Individually-addressable via CMOS driver arrays

[1]*Islim, M.S., et al., Towards 10 Gb/s OFDM-based visible light communication using a GaN violet micro-LED. Photonics Research, 2017.*

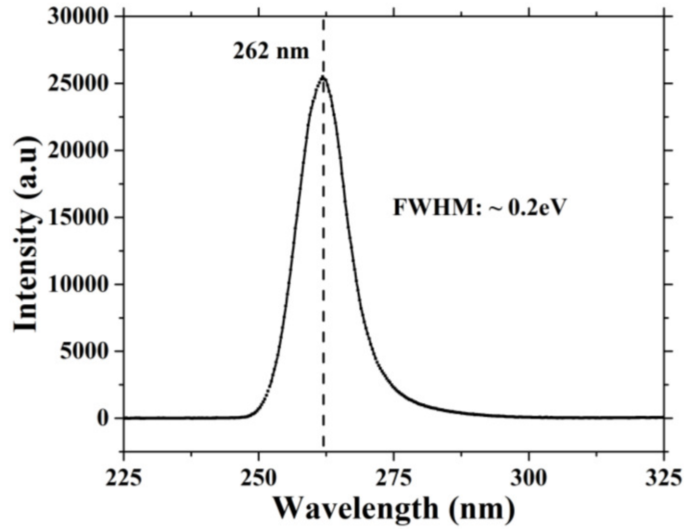
[2]*S. Rajbhandari et al., "A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications", Semicond. Sci. Technol., 32, 023001 (2017).*

Design, fabrication and performance of the UV-C μLED array

GaN based UV-C LED wafer

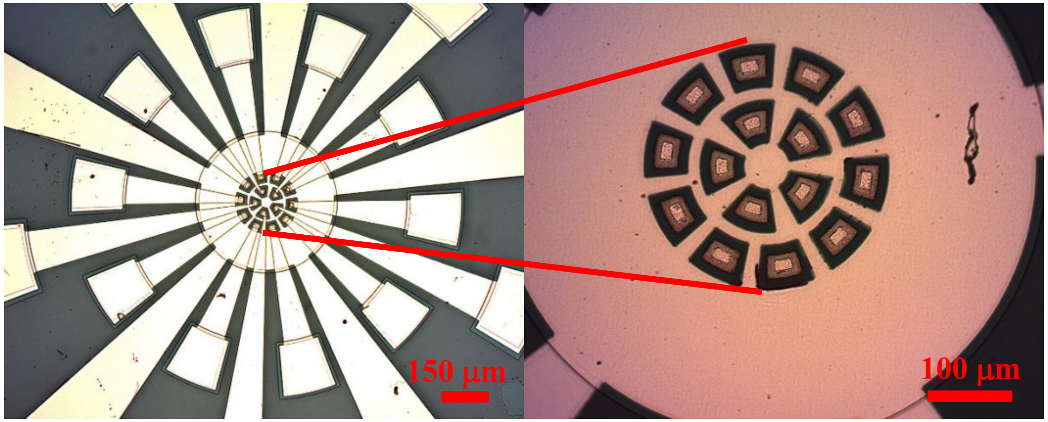


Typical deep UV LED wafer structure[1]



Design of 15-segment array

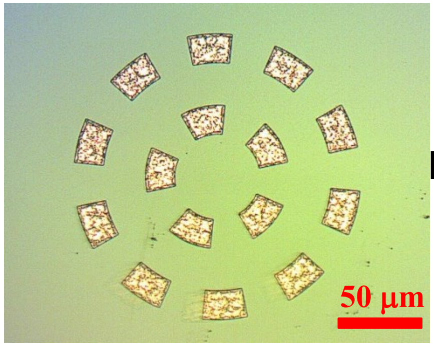
- Flip-chip configuration
- Emission area of each pixel is roughly equal to a circular pixel with a diameter of 26 μm

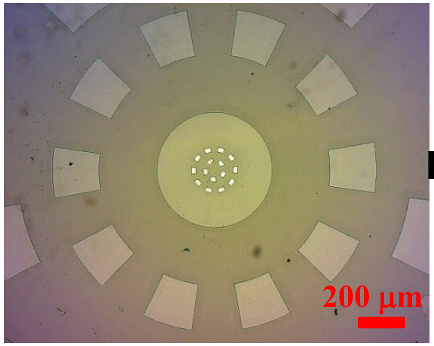


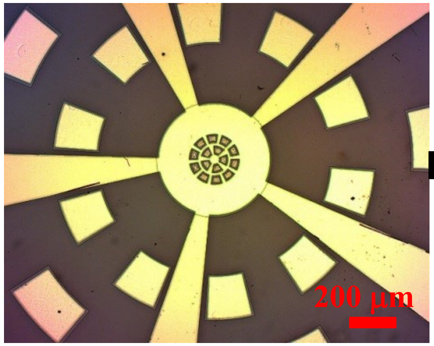
[1]*Zetian, Mi., et al., III-Nitride Semiconductor Optoelectronics. Elsevier Science & Technology, 2017.*

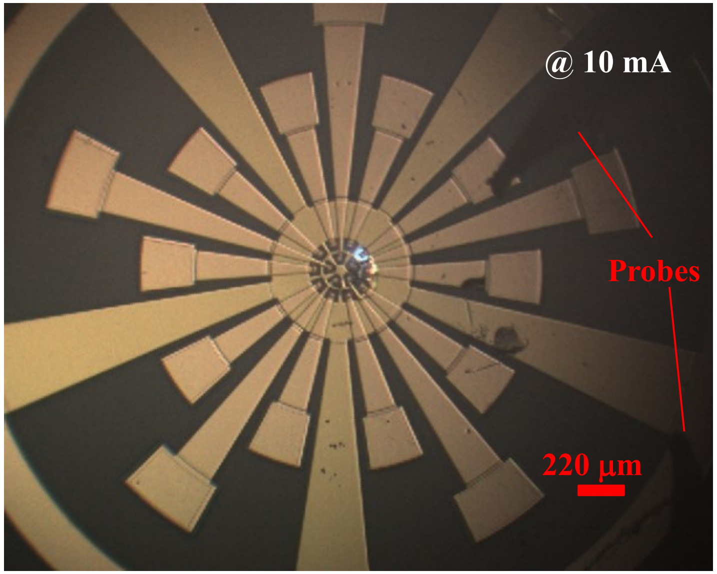
Design, fabrication and performance of the UV-C μLED array

μLED element etching	Mesa and bonding pad etching	N-contact and n-electrode deposition	SiO_2 growth for isolation layer & Metal deposition for p-electrodes



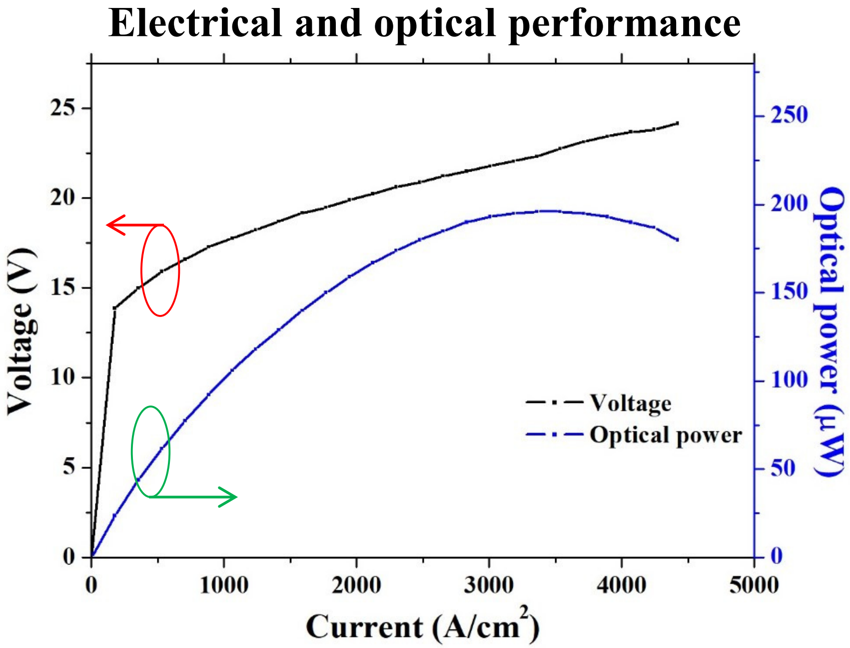


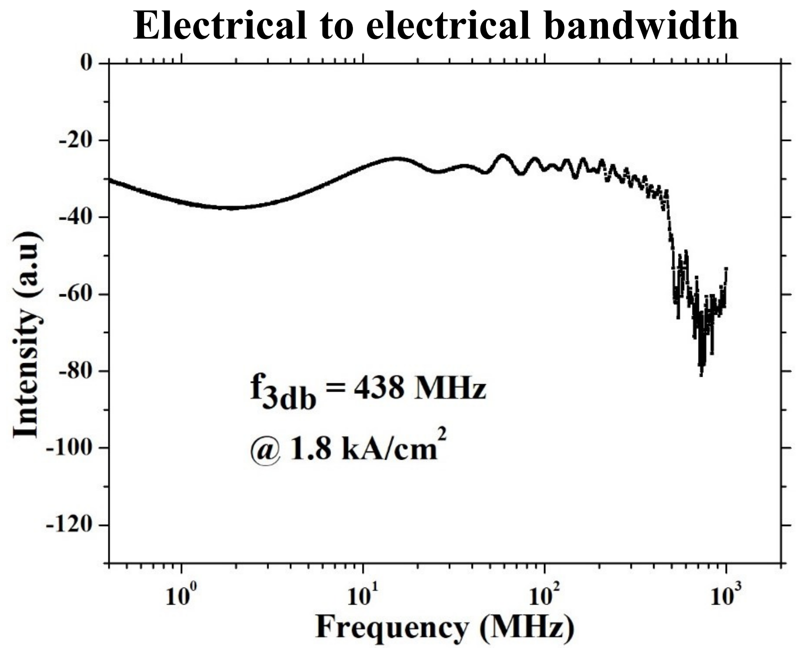




- Pd as p-type contact and reflecting mirror
- Ti/Au as metal track and n-type contact
- Two ICP etching steps to further reduce the capacitance of μLED array

Design, fabrication and performance of the UV-C μLED array





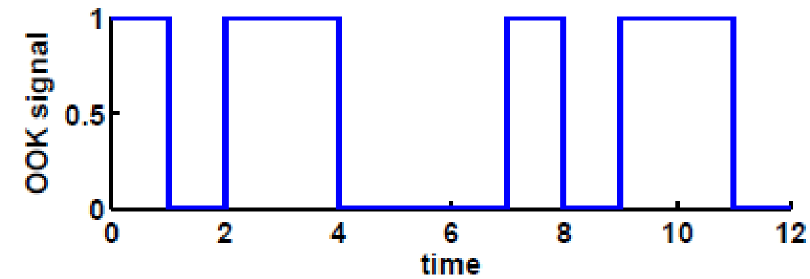
- Over 3.4 kA/cm^2 DC operation current density for a single μLED element (20 mA)
- Over 34 W/cm^2 optical power density for a single μLED element (196 μW)
- Over 400 MHz electrical to electrical modulation bandwidth for a single μLED element at 1.8 kA/cm^2
- Bandwidth performance is limited by the APD detector used

Free-space optical communication based on the UV-C μLED array

Modulation scheme used for optical communication demonstration

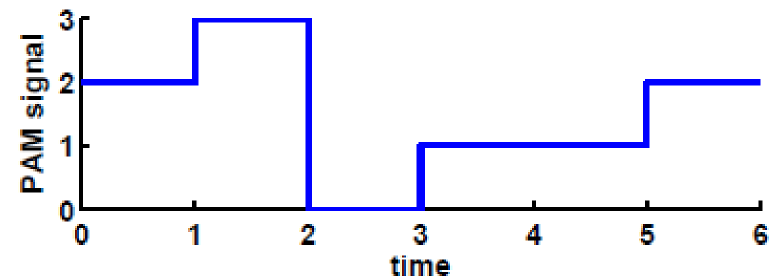
Transmitting binary bit sequences (eg. 101100010110…), usually combined into multi-bit *symbols*

On-Off Keying



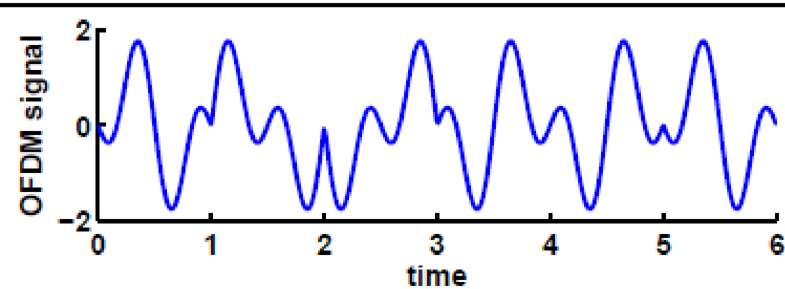
Pulse Amplitude Modulation, 2^n levels

PAM



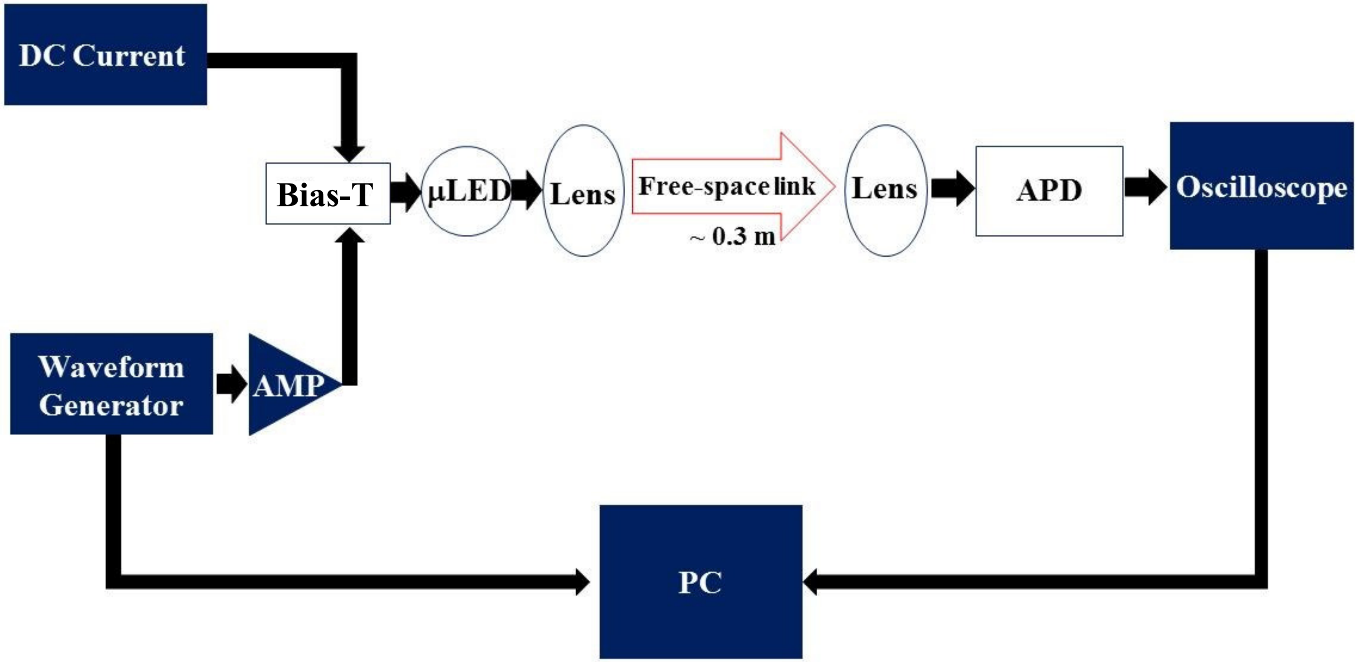
Orthogonal Frequency Division Multiplexing

OFDM



Free-space optical communication based on the UV-C μLED array

Experiment set-up for optical communication



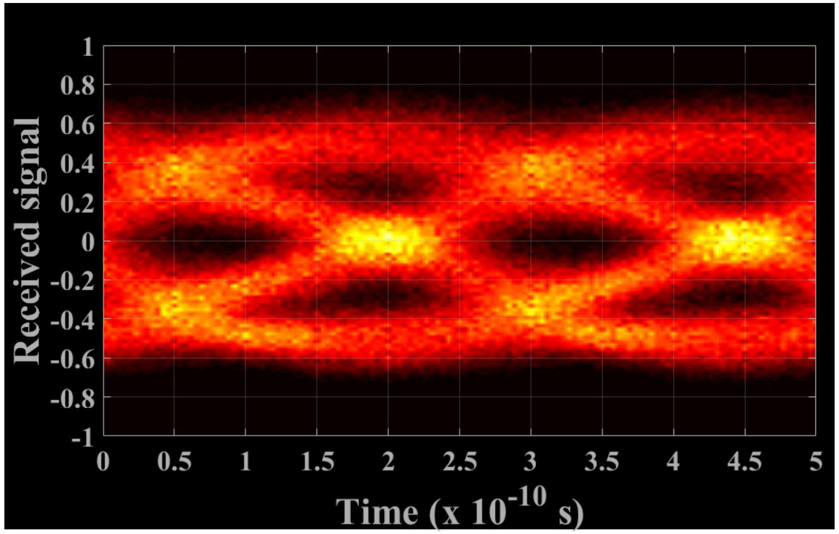
- Waveform Generator: Keysight 81180B
- AMP: ZHL-6A-S+
- Bias-T: SHF BT45-D
- APD detector: APD430A(/M)
- Oscilloscope: MS 07104B

- DC bias of OOK: 8 mA
- DC bias of PAM-4 and OFDM: 10 mA
- Peak to peak voltage of OOK: 2V
- Peak to peak voltage of PAM-4 and OFDM: 7.11 V
- 400 MHz bandwidth used in OOK
- 500 MHz bandwidth used in PAM-4 and OFDM

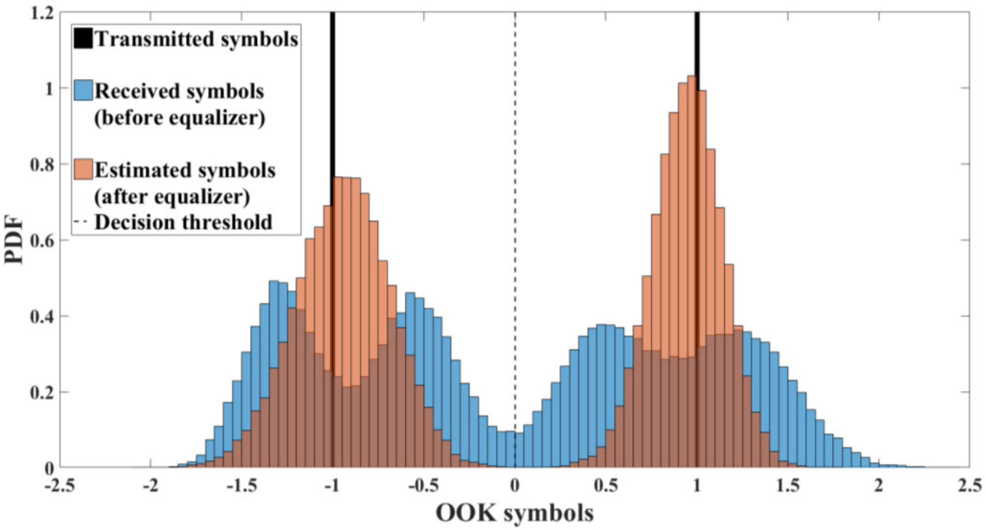
Free-space optical communication based on the UV-C μLED array

OOK @ 800 Mbps

Eye diagram



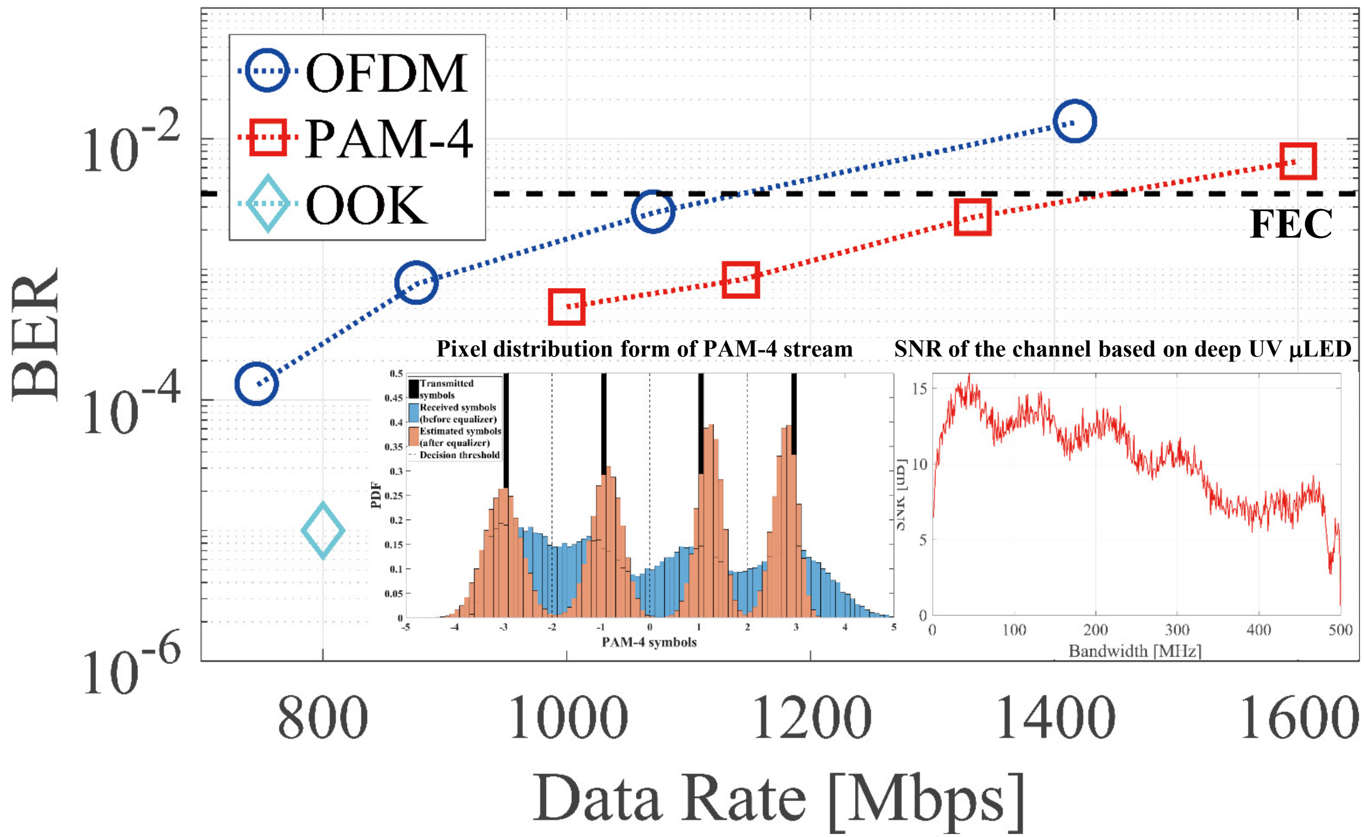
Pixel distribution form



- **Source of distortion: the additive noise, attenuation in the channel, and inter-symbol interference**
- **Adaptive equalizer: based on recursive least squares updating algorithm is used to mitigate the distortion**
- **800 Mbps data rate is achieved at minimum BER using OOK modulation scheme**

Free-space optical communication based on the UV-C µLED array

Data rate of OOK, PAM-4 and OFDM modulation schemes



- 1.1 Gbps data rate is achieved at the forward error correction level using OFDM
- 1.4 Gbps data rate is achieved at the forward error correction level using PAM-4
- The data transmission performance of the UV µLED element is limited by the APD detector

Summary and future work

- ❖ The data rate achieved is more than 10 times higher than previously published work
- ❖ Longer data transmission distance when using a single UV-C LED element as a light source

- ➢ Measured μLED element in this work without heatsink
  - New design to improve the optical power
  - Apply high bandwidth photodetector

Comparison of UV communication system [1]

Light source	Modulation Scheme	Photo Detector	Transmission Power	Channel Length	Data Rate
265 nm mercury-xenon lamp	PPM	PMT	25W	1.6 km	1.2 Mbps
253 nm mercury-argon lamp	PPM	PMT	5W	0.5 km	10 kbps
253 nm low pressure mercury lamp	FSK	PMT	-----	6 m	1.2 kbps
265 nm LED arrays	OOK/PPM	PMT	43 mW	10 m	2.4 kbps
294 nm LED	OFDM	APD	190 μW	8 cm	71 Mbps
262 nm μLED	PAM-4/OFDM	APD	196 μW	30 cm	>1 Gbps

- **PPM:** pulse-position modulation
- **PMT:** photomultiplier tube
- **FSK:** Frequency-shift keying

[1]*Xiaobin, Sun., et al., 71-Mbit/s ultraviolet-B LED communication link based on 8-QAM-OFDM modulation. Optical express, 2017.*

Acknowledgements

ULTRA
PARALLEL
VISIBLE
LIGHT
COMMUNICATIONS

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/K00042X/1 “**Ultra-parallel Visible Light Communications**”

up-vlc.photonics.ac.uk