高速氮化镓基可见光收发器件与芯片技术

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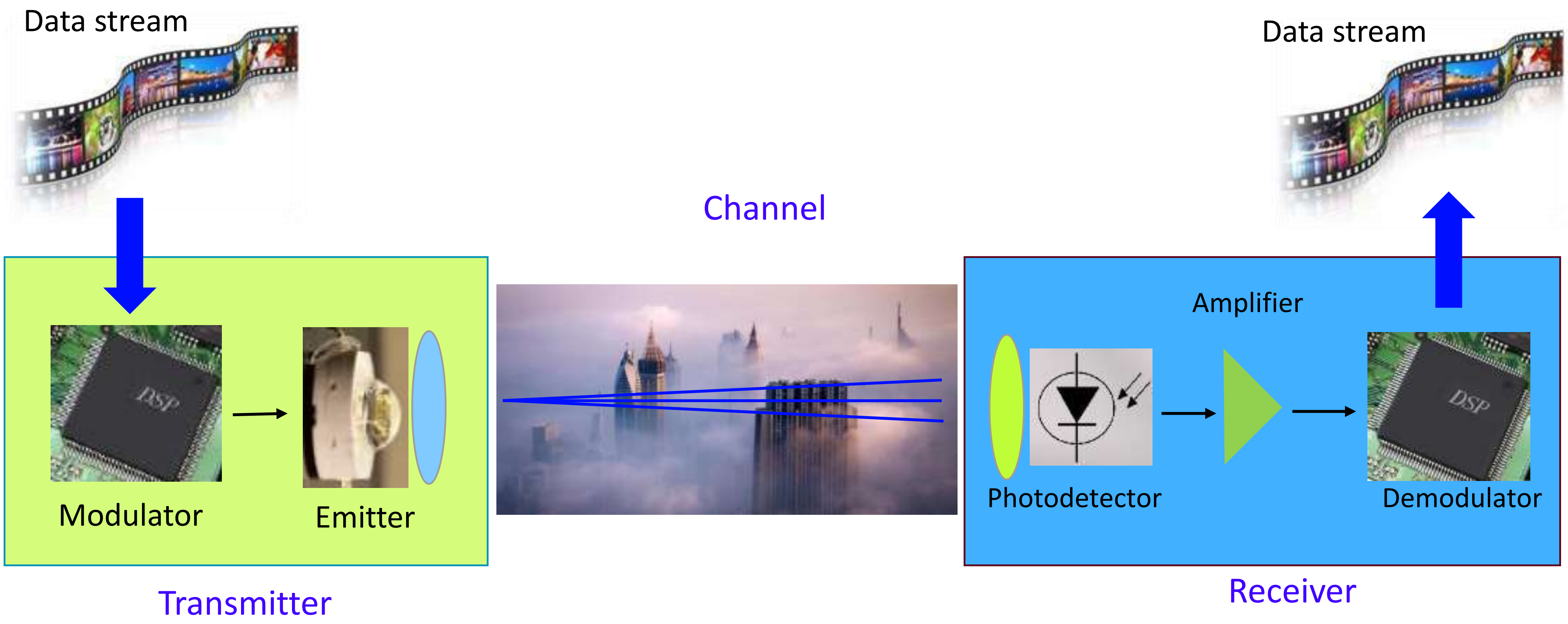
2021年7月

Outline

- Intro
- Transmitter Technology
- Photonics Integration
- Receiver Technology
- The end

Structure of a VLC Link



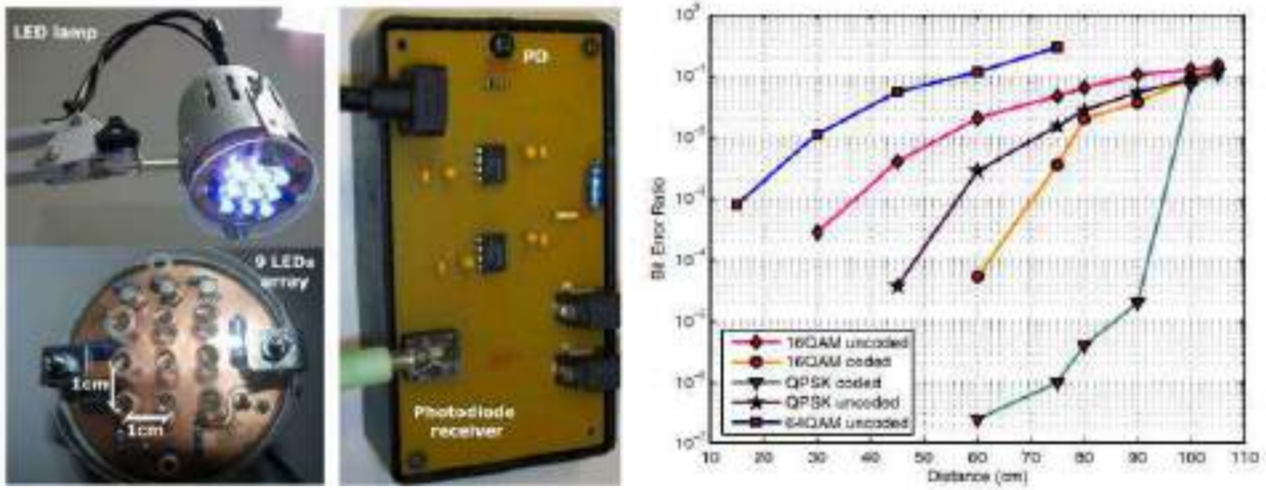
VCL link consists of

- Transmitter: high modulation speed emitter
- Channel: distance, condition like dusty or foggy, LOS or Non-LOS
- Receiver: high speed detector + demodulator

The "Blue LED" Revolution

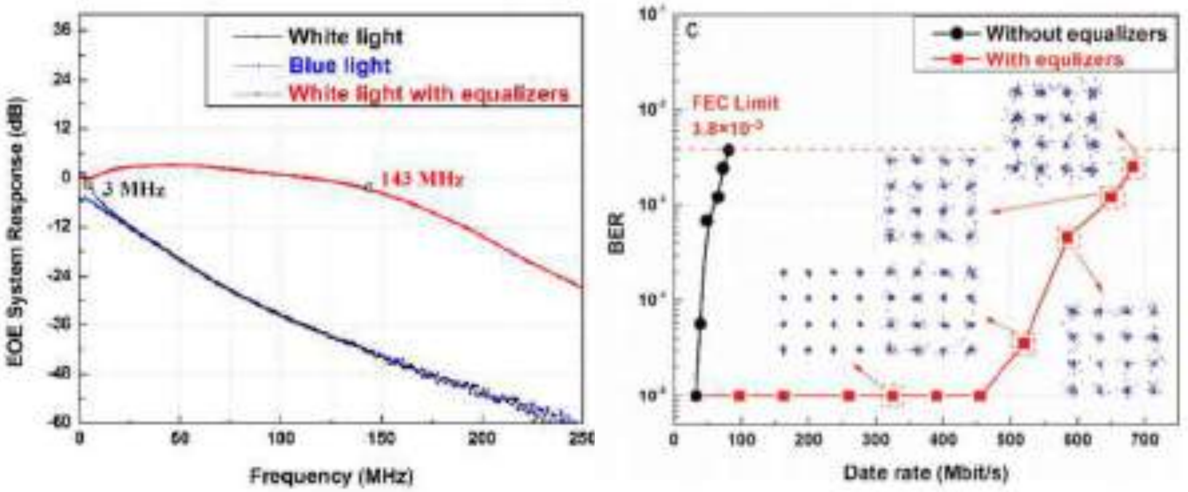
Transmitter – Light Emitting Diode (LED)

Indoor broadcasting via white LEDs and OFDM



H. Hass et al., IEEE Transactions on Consumer Electronics, 55 (3), August 2009
H. Hass et al., in IEEE 65th Vehicular Technology Conference, 2007

682 Mbit/s phosphorescent white LED VLC system

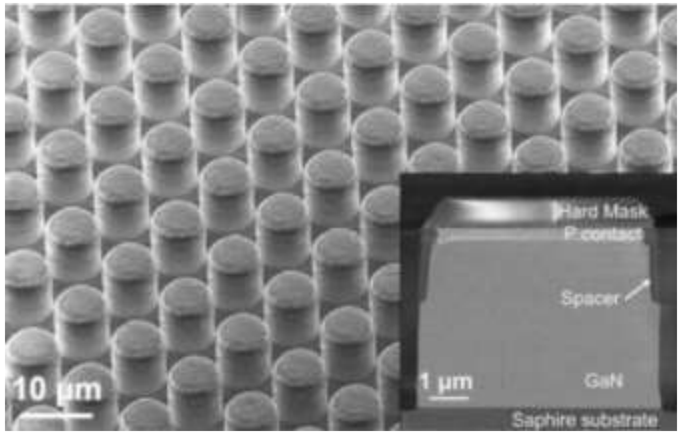


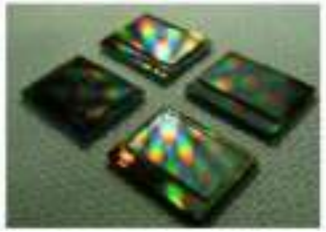
Chen et al., Optics Communication, 354, 107-111, May 2015

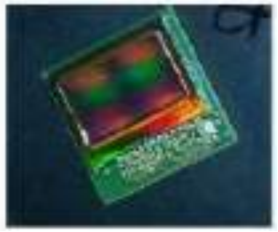
- Advantage of LED
  - ✓ Long Lifetime: ~ tens of thousands hours
  - ✓ Compact: ~ µm
- Disadvantage of LED for VLC system
  - ✓ Limited modulation bandwidth
  - ✓ Efficiency droop for illumination

Transmitter – Micro-Light Emitting Diode (µLED)

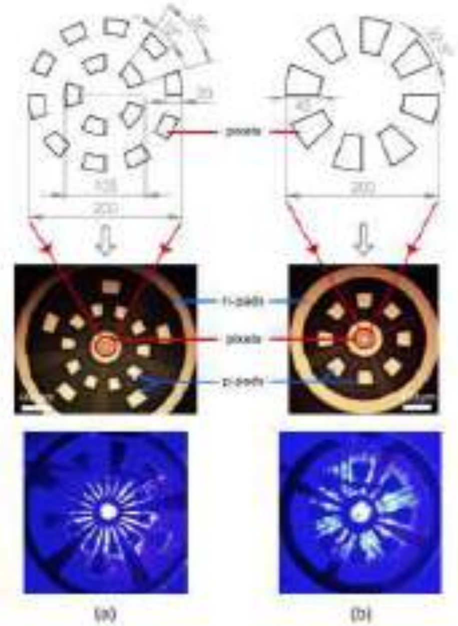
Wafer-level micro-LED matrix delivers high brightness at 2540dpi

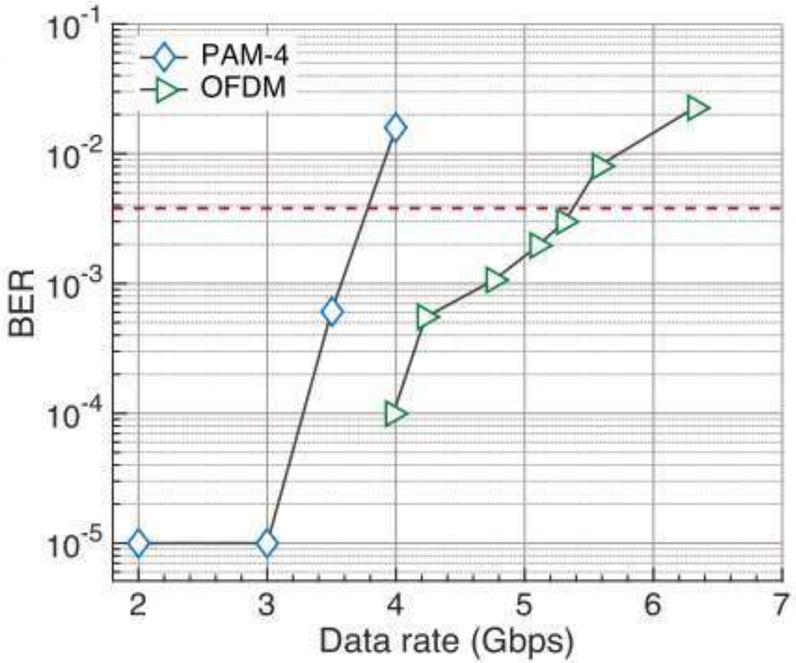






F. Templier, et at., Proc. SPIE 10104, Gallium Nitride Materials and Devices XII, 1010422 (2017)
SPIE OPTO, SPIE, 2018, p. 6. (Grenoble-France)



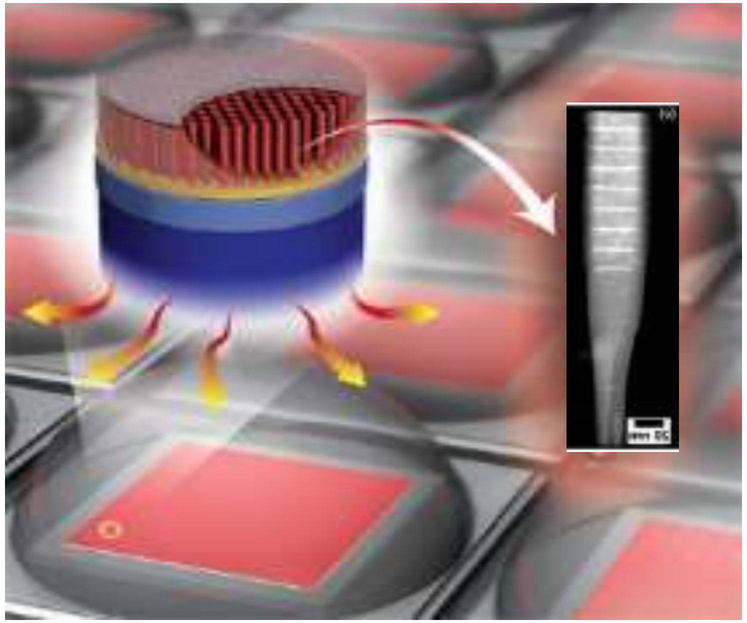


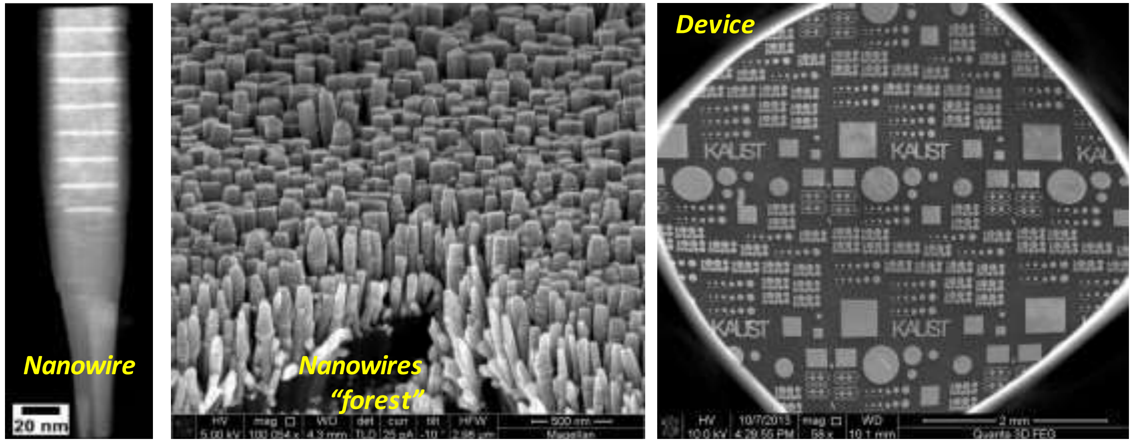
IEEE Photonics Technology Letters, 28 (19), October 2016
(Strathclyde, Glasgow & Oxford)

Improved bandwidth with smaller LED size

✓ 3.5 Gbps (PAM-4) and 5 Gbps (adaptive DCO-OFDM)

Transmitter – Nanowire LED



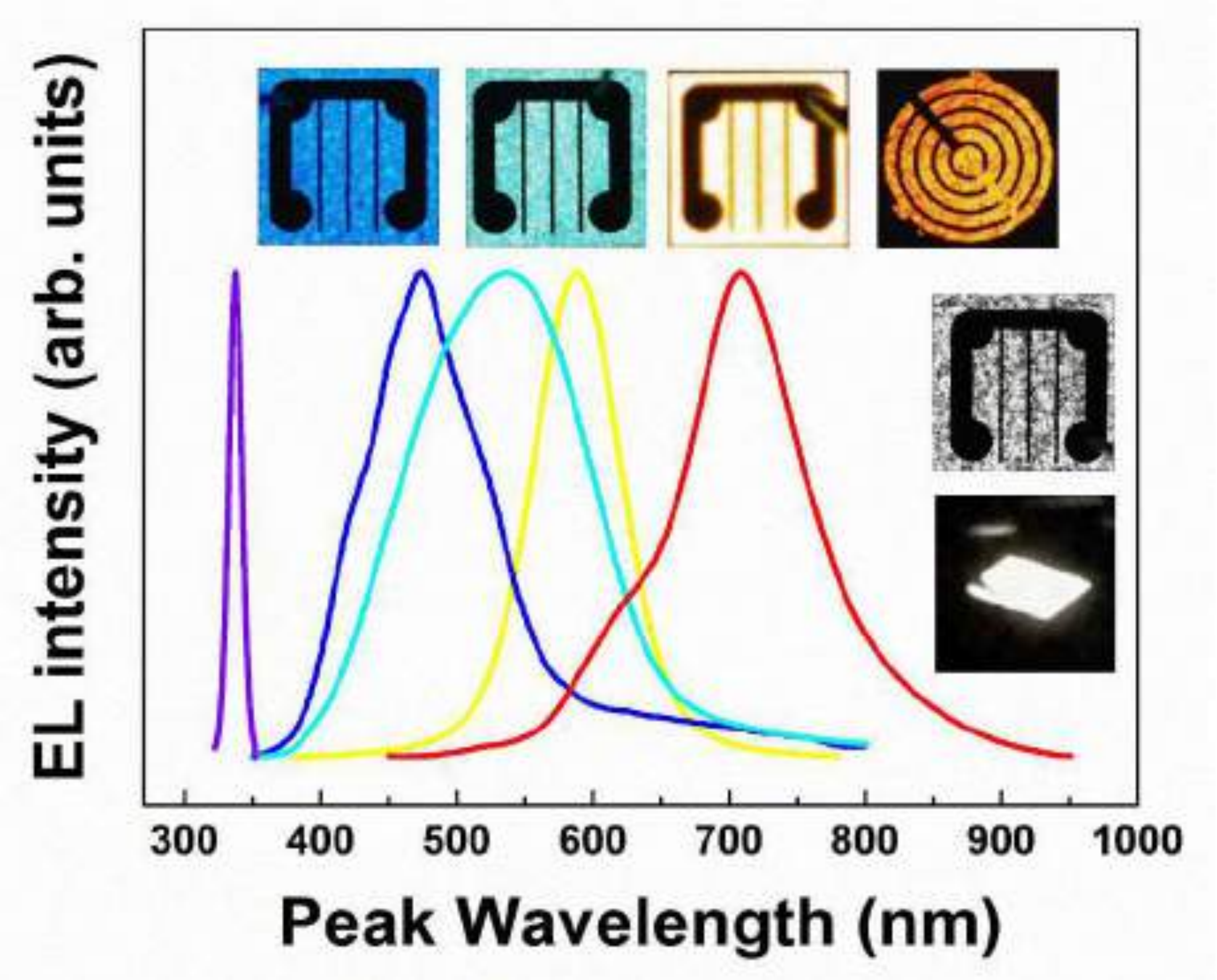


- Successfully growth of GaN nanowire LED on metal substrate.
- Metal serves as the device supporting material, electrical contact, heat-sink and light reflector.
- No efficiency droop is observed from these devices.

ACS Energy Letters, January ***2018***
Small, 12, 2312, ***2016***
Nano Letters, January ***2016***
Advanced Materials, March ***2016***
Nano Letters, July ***2016***

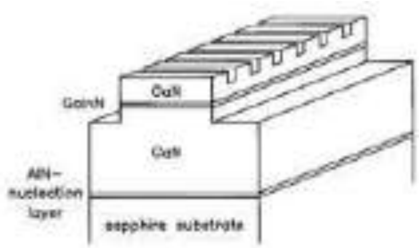
NW LED for multiple wavelength integration

UV, BLUE, GREEN, YELLOW, RED, & WHITE LEDS



Progress in Quantum Electronics (2018)
Nanoscale (2018)
Nano Letters (2018)
J. Nanophotonics (2018)
ACS Photonics (2017)
Applied Physics Letters (2017)
Optical Materials Express, 7, 4214 (2017)
Nanoscale 9, 7805 (2017)
RSC Advances, 7, 26665 (2017)
Optics Express, 25, 1381 (2017)
Nano Letters, 16, 1056 (2016)
Nano Letters, 16, 4616 (2016)
Advanced Materials, 28, 5106 (2016)
Small, 12, 2313 (2016)
ACS Photonics, 3, 2089–2095 (2016)
Optics Express, 17, 19928 (2016)

Progress on III-Nitride Distributed Feedback (DFB) Laser Diodes

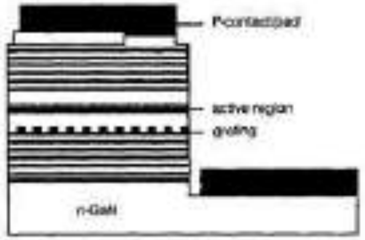


First GaN-based DFB laser

R. Hofmann, H. Schweizer et al.
Univ. Stuttgart
Appl. Phys. Lett. ***69*** *(14)*
1996

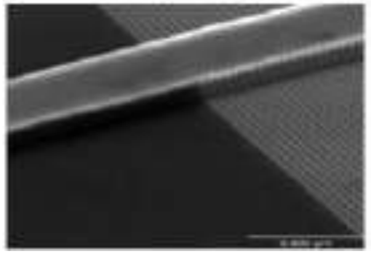
Electrically injected DFB laser

D. Hofstetter, M. Kneissl, et al.
Xerox Palo Alto Research Center
Appl. Phys. Lett. ***73*** *(15)*
1998



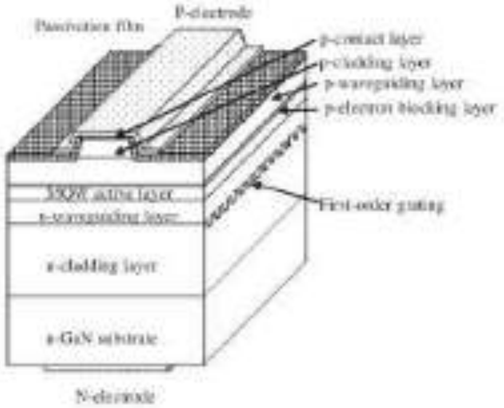
Embedded DFB gratings

A.C. Abare, M. Hansen, J.S. Speck,
S.P. DenBaars, L.A. Coldren
Univ. of Cal. Santa Barbara
Electron. Lett. ***35*** *(18)*
1999



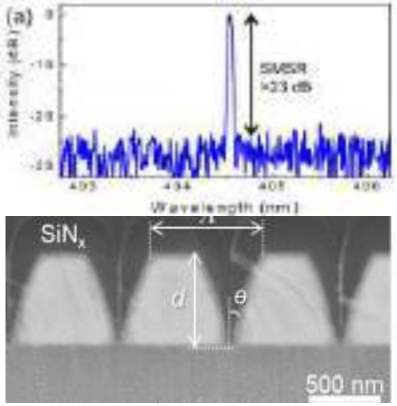
Laterally coupled DFB gratings

H. Schweizer, et al
Univ. Stuttgart and OSRAM
Phys. Stat. Sol. (a) ***192*** *(2)*
2002



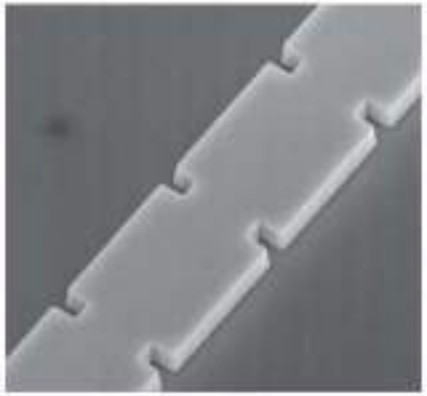
CW first-order DFB laser

S. Masui, et al. NICHIA
Jap. J. Appl. Phys. ***45*** *(46)*,2006



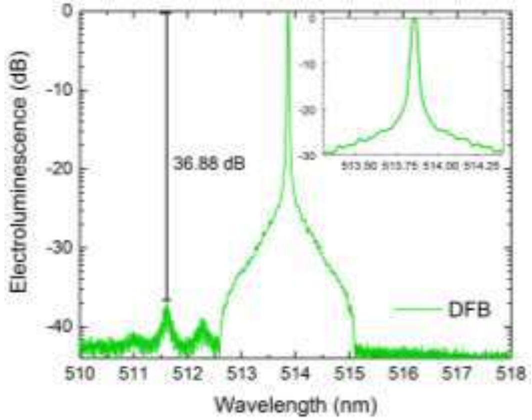
Beyond 20 dB Side-mode suppression ratio

J.H. Kang, T. Wernicke, M. Kneissl et al.
Ferdinand Braun Inst. Tech.Univ. Berlin,
IEEE Phot. Tech. Lett. ***30*** *(3)*
2018



Ridge sidewall gratings, CW, 35 dB SMSR

T.J. Slight, A.E. Kelly, P. Perlin, M. Leszczynsky, et al. Compound Semi. Tech. Global, Topgan, Unipress, Univ. Glasgow, Aston Univ. Appl. Phys. Exp. ***11*** *(112701)*
2018

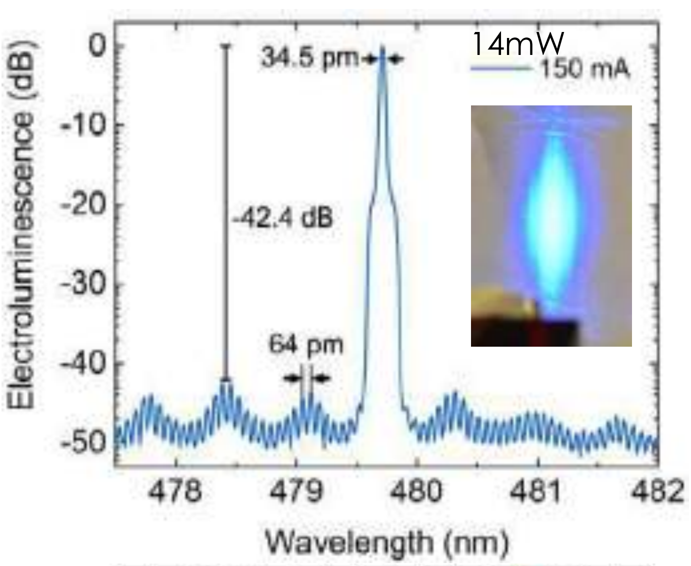


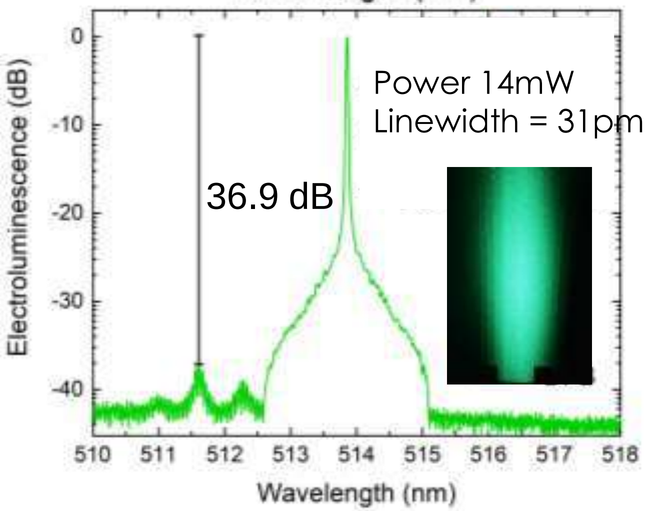
First InGaN green DFB laser

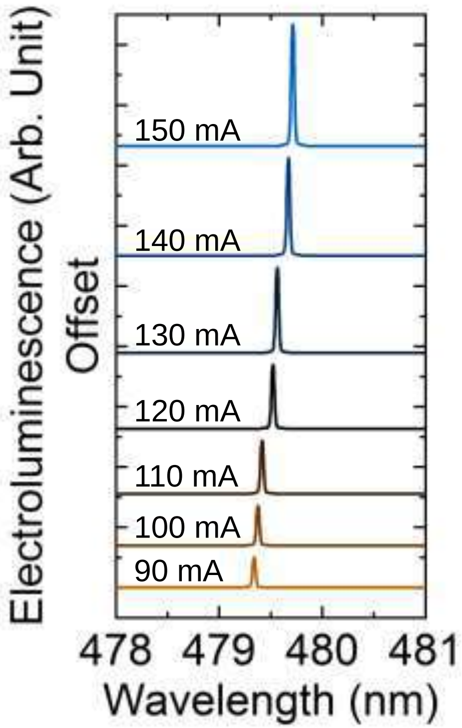
B.S. Ooi, et al. KAUSTAppl. Phys. Exp. ***12*** *(042007)*,2019

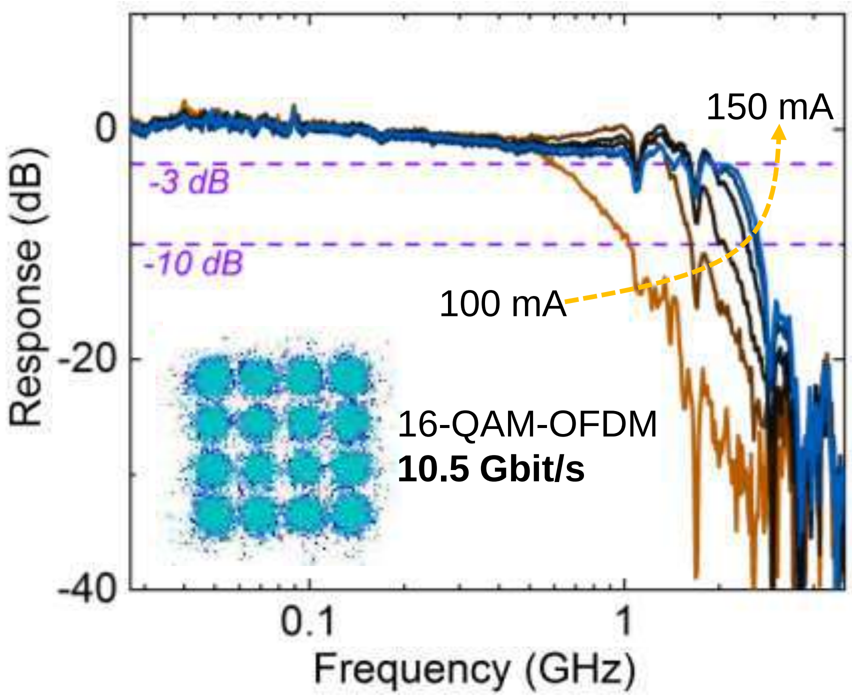
GaN-based DFB Laser Characterizations

First demonstration of GaN DFB emission at sky-blue and green colors









Record fastest for any GaN DFB laser

Record side-mode suppression ratio (SMSR) for GaN DFB laser

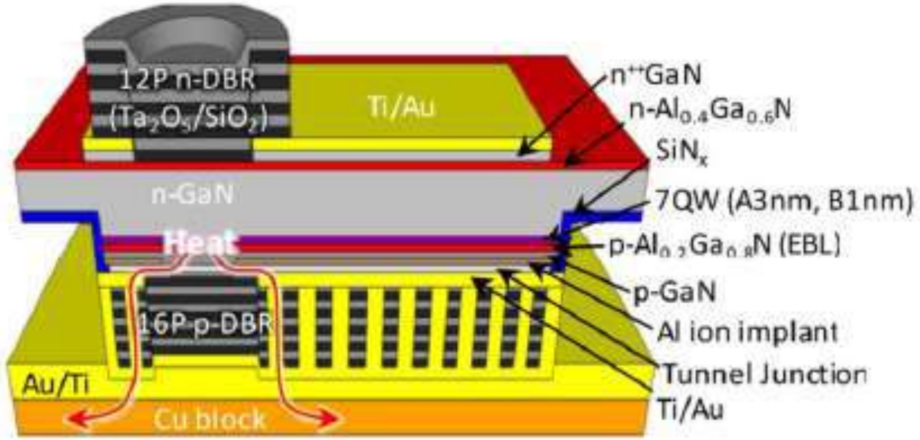
Opt. Lett. 45(3), 742 (2020)
Appl. Phys. Express 12(4), 042007 (2019)

Proc. of SPIE 11301, 1130104 (2020)

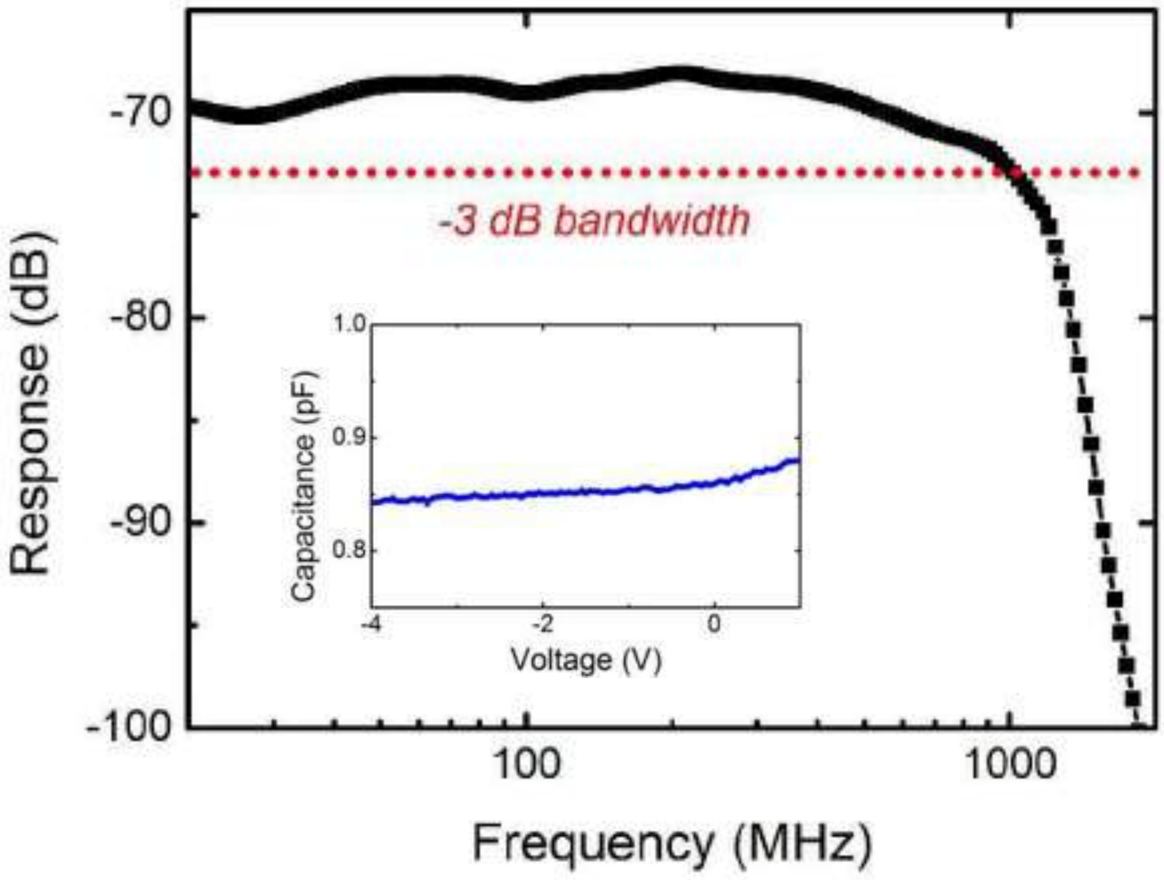
OFC Conf. T3C.3 (2020)

InGaN VCSEL

Schematic of *m*-plane InGaN VCSEL



- Ta_2O_5/SiO_2 Dual-DBR mirrors.
- Al ion implanted aperture of 10 μm.
- PEC etched substrate removal.
- Flip-chip bonding.
- Tunnel junction intracavity contact.



<u>Sub-pF</u> (~0.85 pF) junction capacitance

<u>Threshold current of 18 mA, corresponding to a threshold voltage of 7.5 V. Slope efficiency of 7.74 μW/mA.</u>

<u>The maximum frequency response of the presented 10-μm-aperture VCSEL is expected to exceed 1 GHz, although the current result is limited by the BW of the APD.</u>

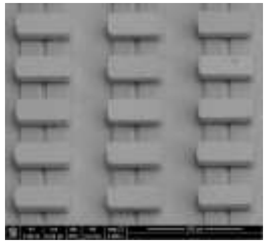
J. T. Leonard, et,al. Appl. Phys. Lett., 2015
C. Shen et, al. CLEO, 2016

GaN-based Light emitters

Shen, et,al., Opt. Express, 23(6), 7991, 2015

Light-emitting diode (LED)

- Spontaneous emission
- Efficiency droop
- 3-dB bandwidth: <100 MHz



Shen, et,al., ACP, 2014

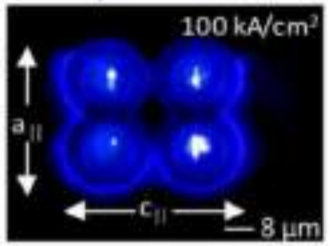
Micro-LED

- Array integration
- High speed
- Relatively low power

Shen, et,al., ACS Photonics, 3 (2), 262, 2016; Opt. Express, 24 (22), 25502, 2016

Laser diode (LD)

- Stimulated emission
- Droop-free
- 3-dB bandwidth: > GHz



Shen, et,al., CLEO, 2016

VCSEL

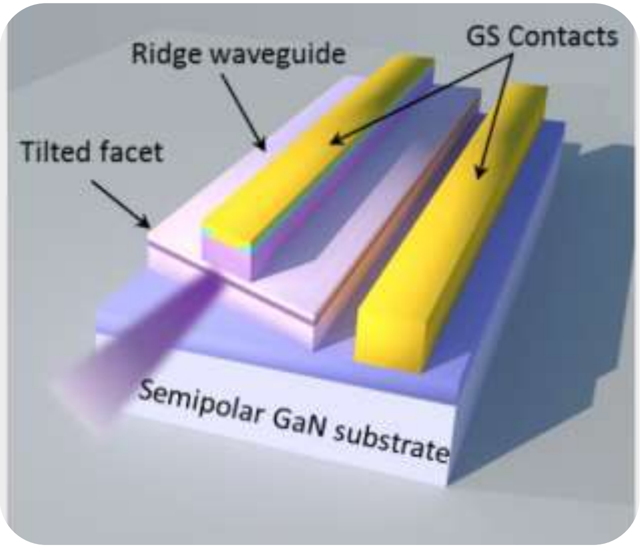
- High quality beam
- Ultra-high speed
- Process challenges

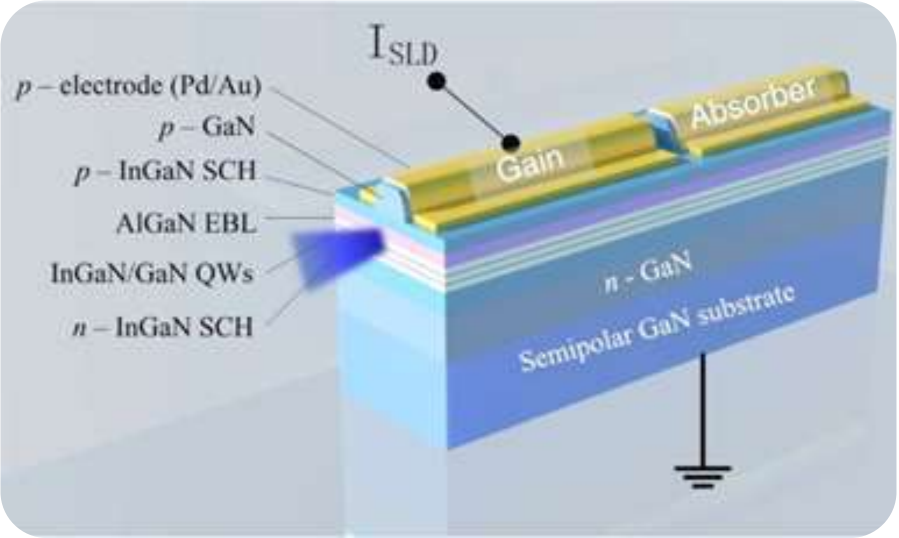
Shen, et,al., Opt. Lett., 41(11), 2608, 2016; Opt. Express, 24 (18), 20281, 2016

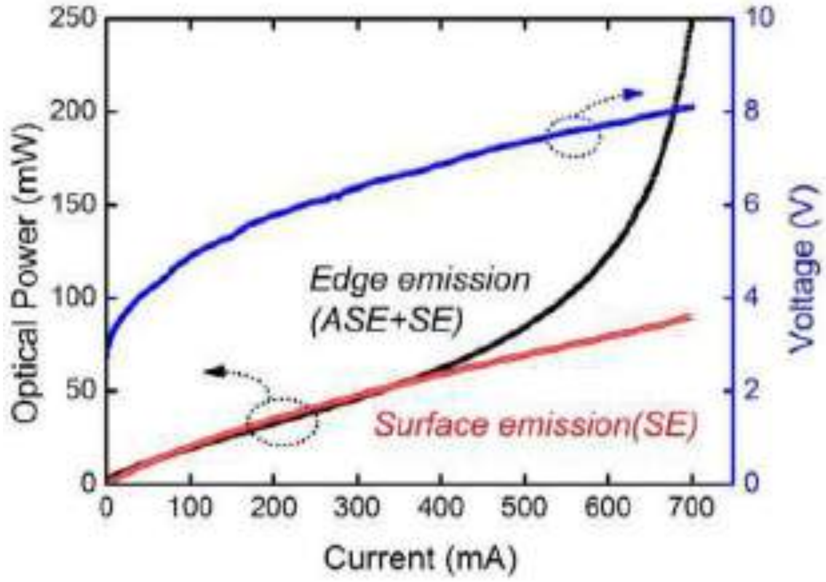
Superluminescent diode (SLD)

- Amplified spontaneous emission
- Droop-free, speckle-free
- 3-dB bandwidth: ~ GHz

Semipolar superluminescent diodes (SLDs)

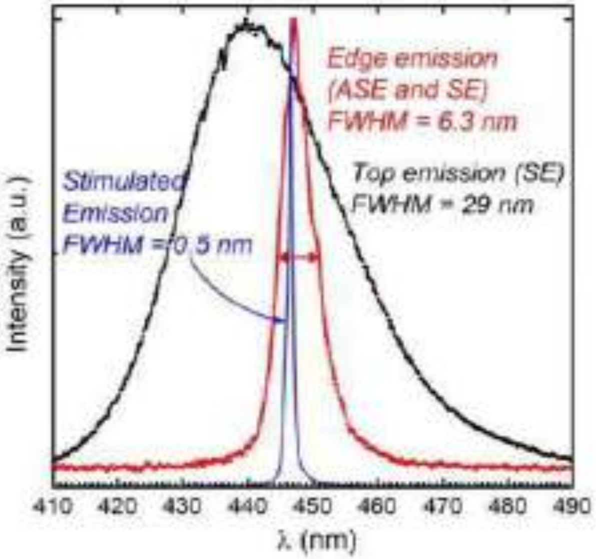






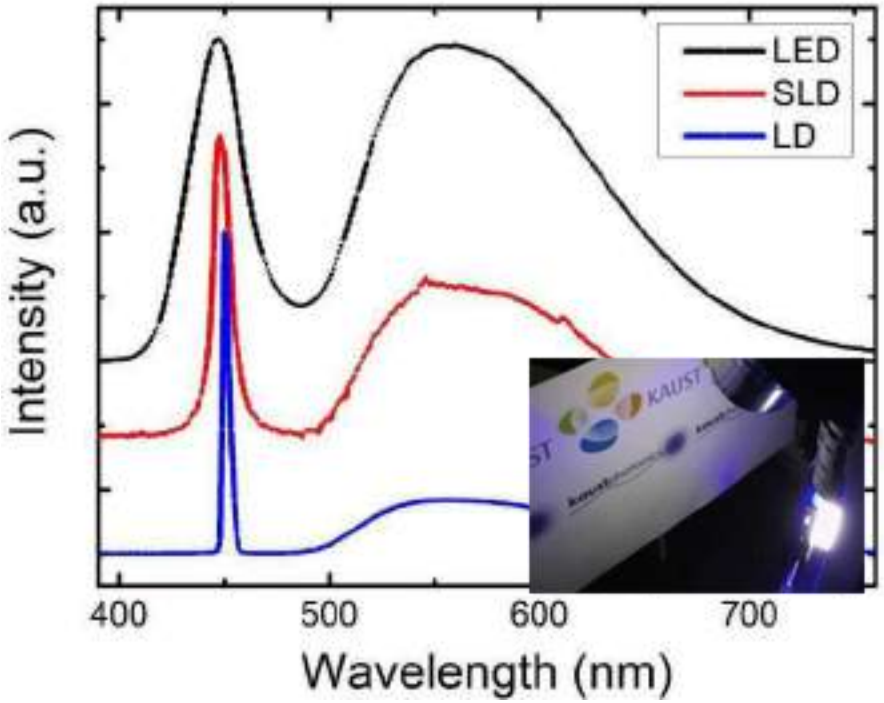
- Tilted facet configuration
- Passive absorber configuration

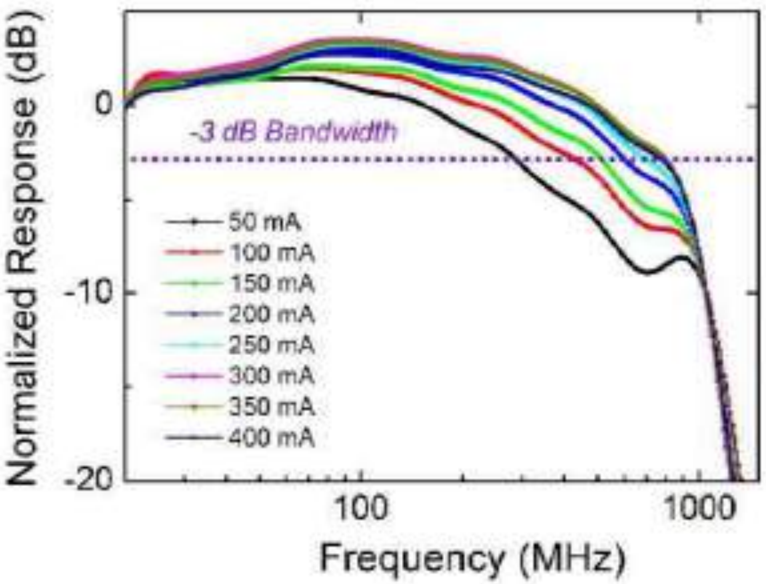
- Optical powers of 123 mW at 600 mA and 256 mW at 700 mA.
- Onset of superluminescence at 400 mA.
- Unlike LED, SLD is free of efficiency droop.

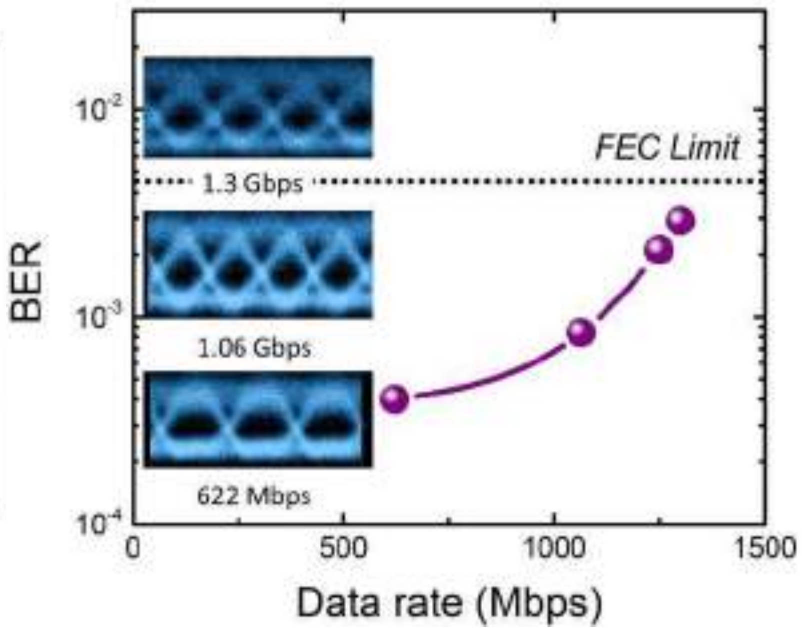


C. Shen, et,al. Optics Express, 2016
C. Shen, et,al. Optics Letters, 2016
C. Shen, et,al. Proc. SPIE, 2017

SLD for SSL and VLC



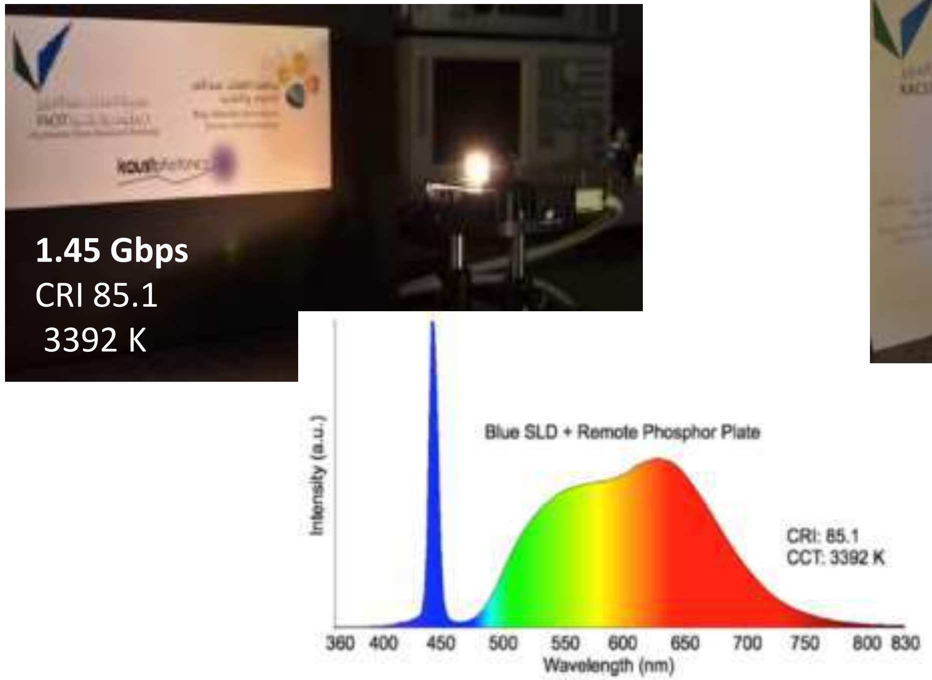


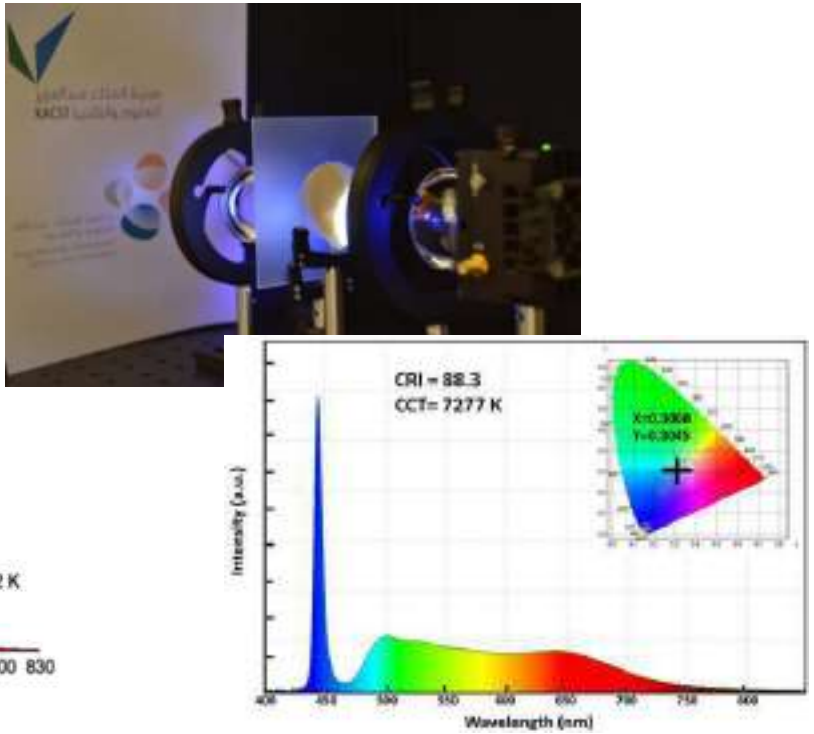


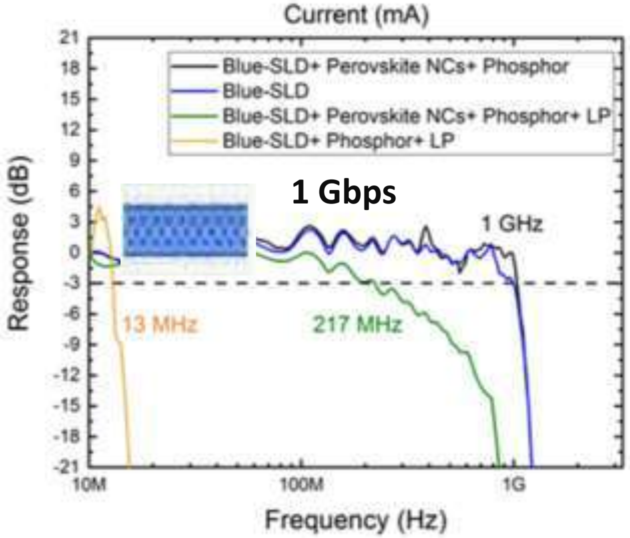
- The **first** report of utilizing SLD for SSL: InGaN based SLD is feasible for white light generation.
- The **first** investigation of high-frequency response of InGaN-based SLDs: > 800 MHz bandwidth.
- The **first** report of SLD based data communication achieving 1.3 Gbps data rate using OOK.

C. Shen, et,al. Optics Express, 2016
C. Shen, et,al. Optics Letters, 2016
C. Shen, et,al. Proc. SPIE, 2017

SLDs for LiFi







- Record SLD optical peak power of 475 mW
- High-performance C-plane SLD: suitable for industry adoption

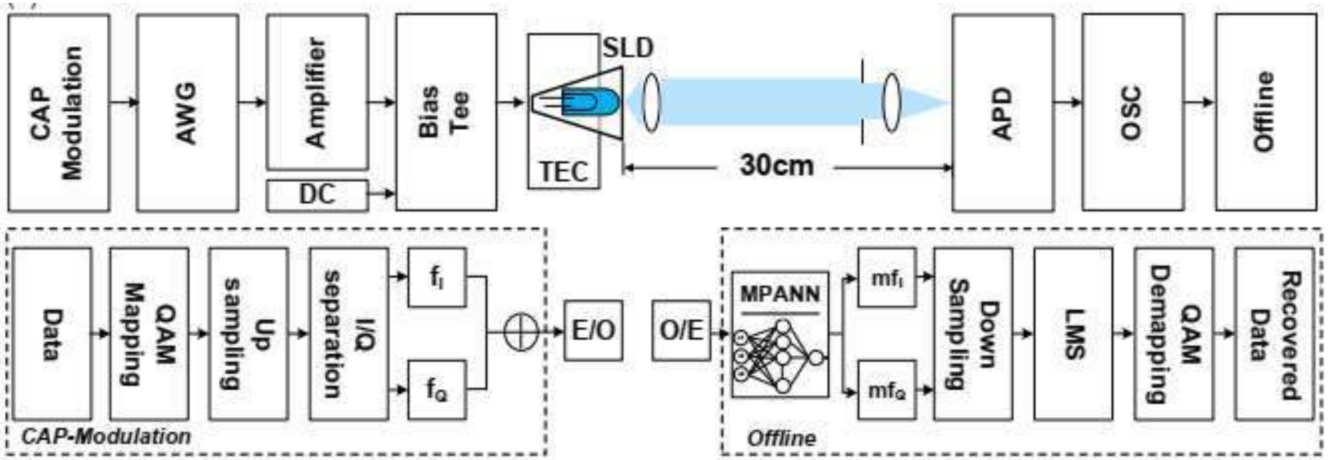
A. Alatawi, J. Holguin-Lerma, Opt. Express, (2018).

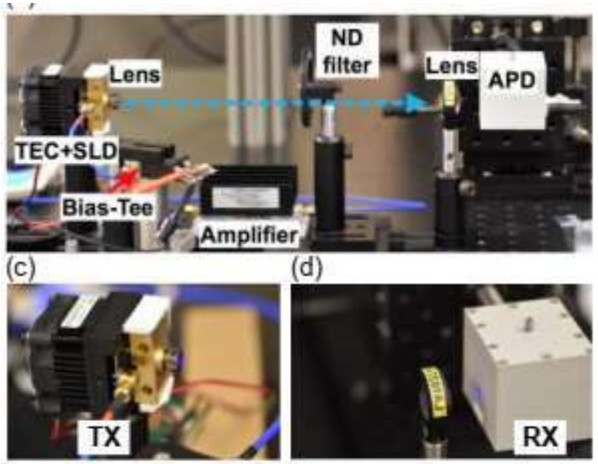
- First report on c-plane SLD + Perovskite-phosphor
- High quality white light of 88.3 CRI and 7277 K CCT
- High modulation bandwidth of 1 GHz

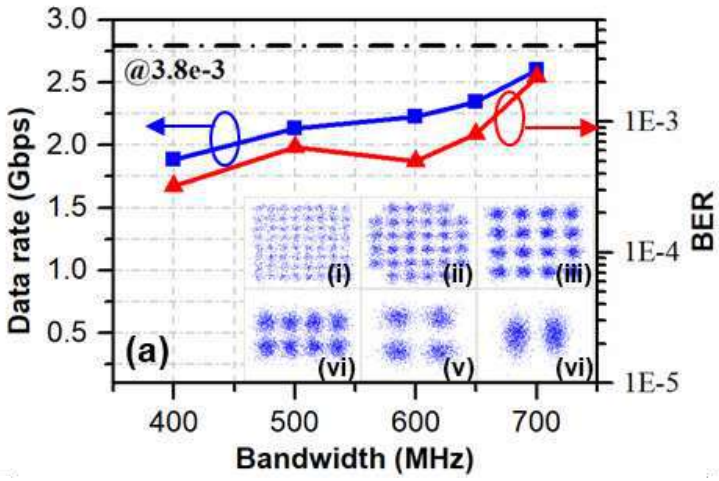
A. Alatawi, et al., 2019.

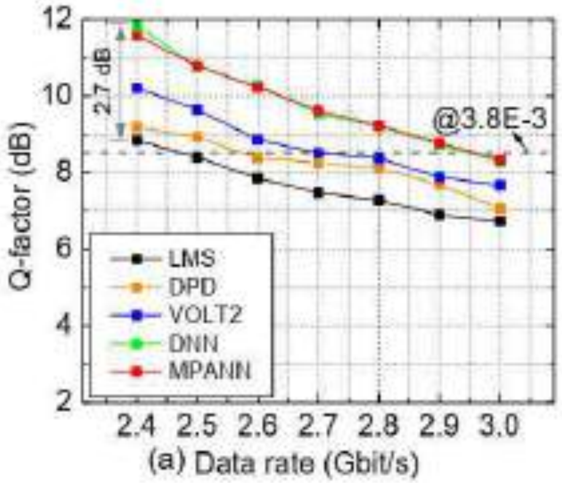
SLD based VLC with MPANN-aided CAP post-equalizer

- Using Memory-Polynomial-aided Neural Network to replace the traditional finite impulse response (FIR) post-equalization filters.
- 2.95-Gbit/s transmission using carrierless amplitude and phase modulation.





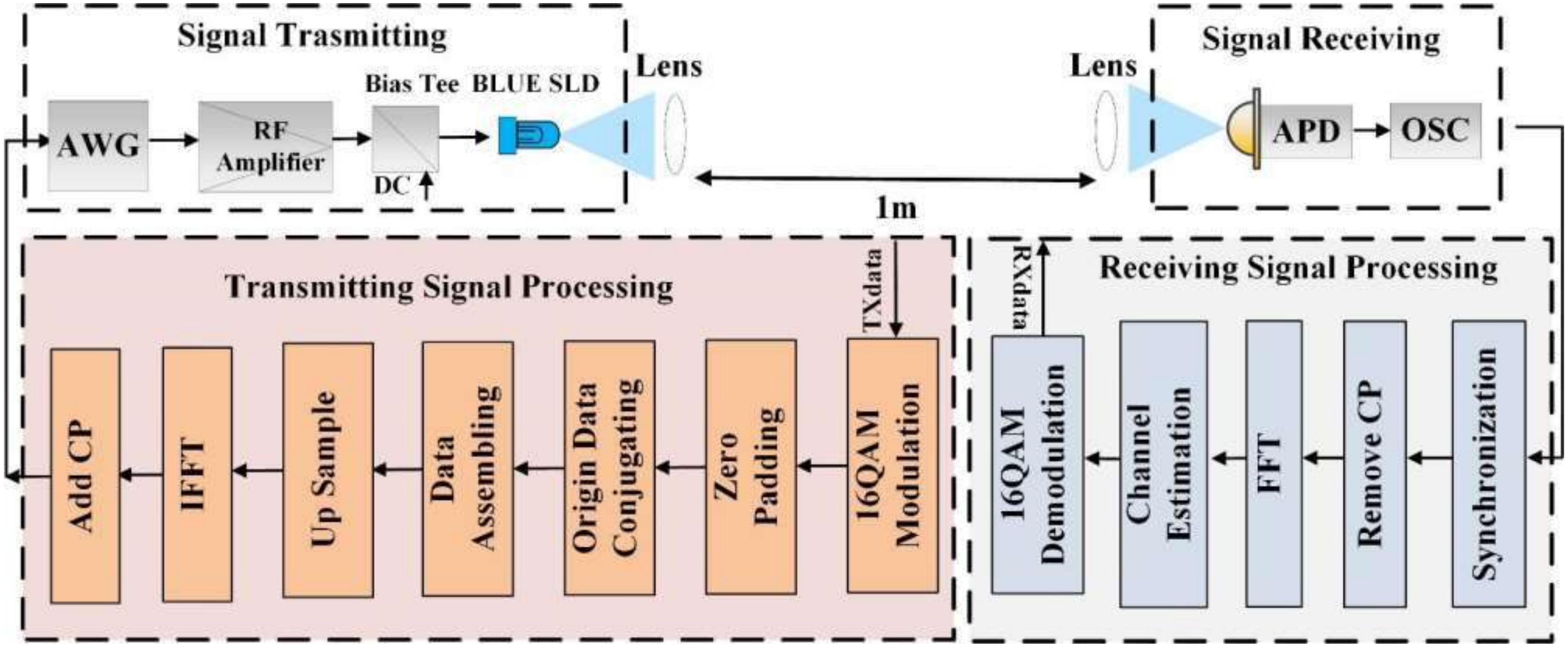




F. Hu et al., ECOC 2019,
F. Hu et al., Opto-Electronic Advances, 2020. (Cover)

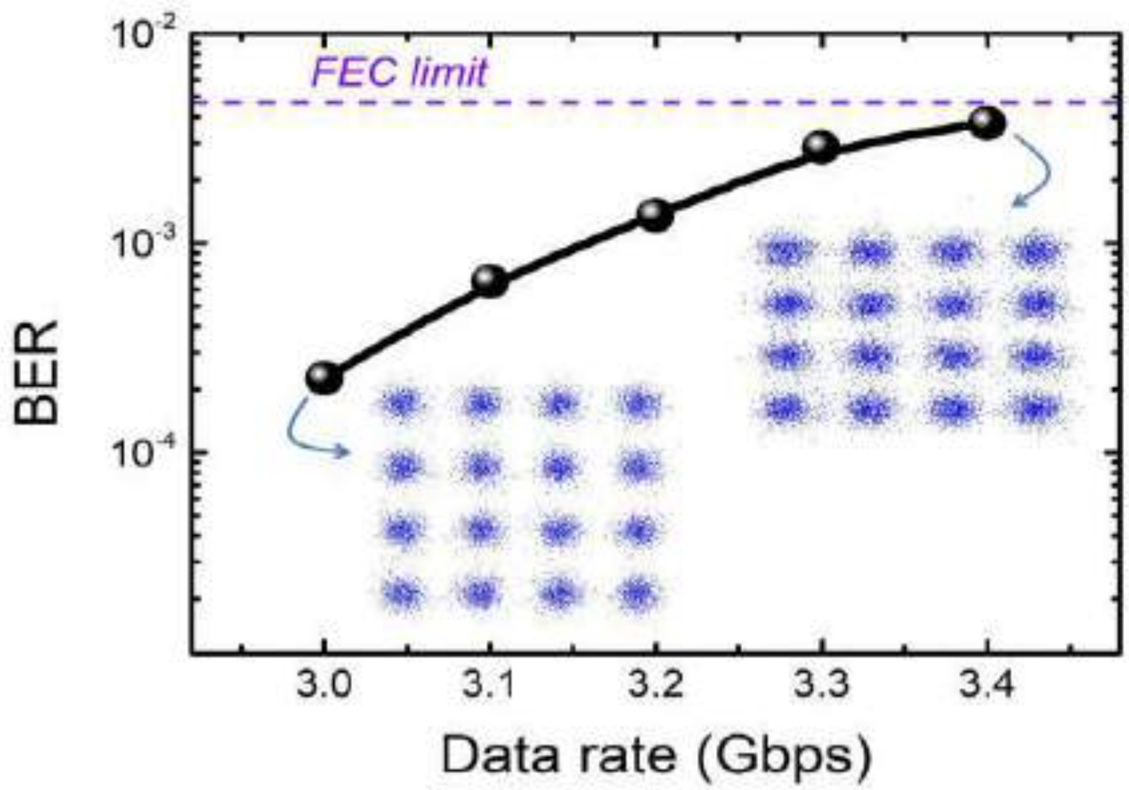
SLD based VLC using OFDM

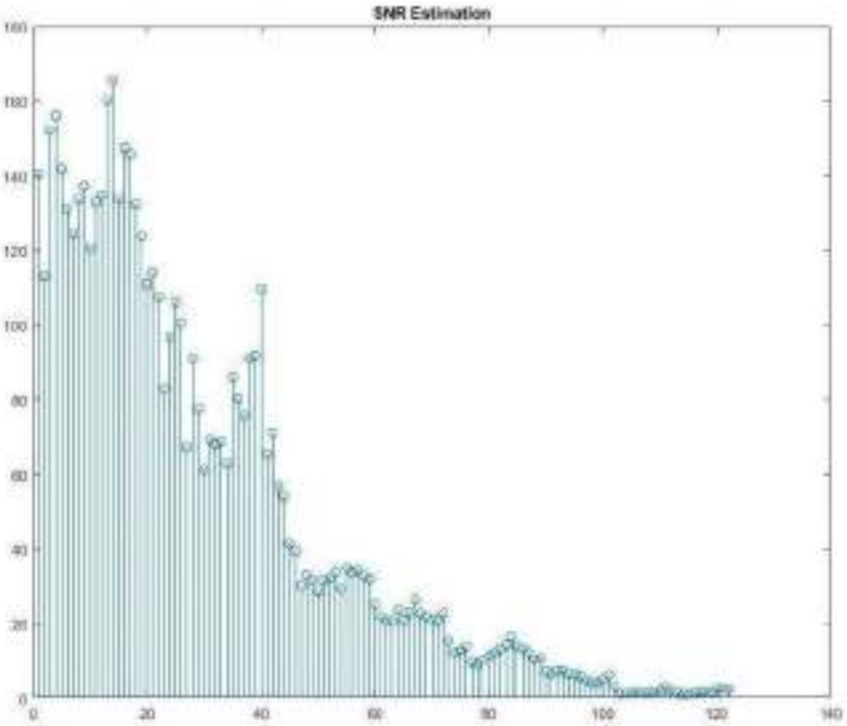
Using 16 QAM DMT for high-speed data transmission



C. Shen et al., IEEE JSTQE (invited paper), 2019.

SLD based VLC using OFDM





At 3.4 Gbps, the blue SLD based VLC system shows a BER of 3.73×10^{-3}.

C. Shen et al., IEEE JSTQE (invited paper), 2019.

Outline

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- The end

InP-based PIC: Realizing low-cost, –size, -weight, and -power

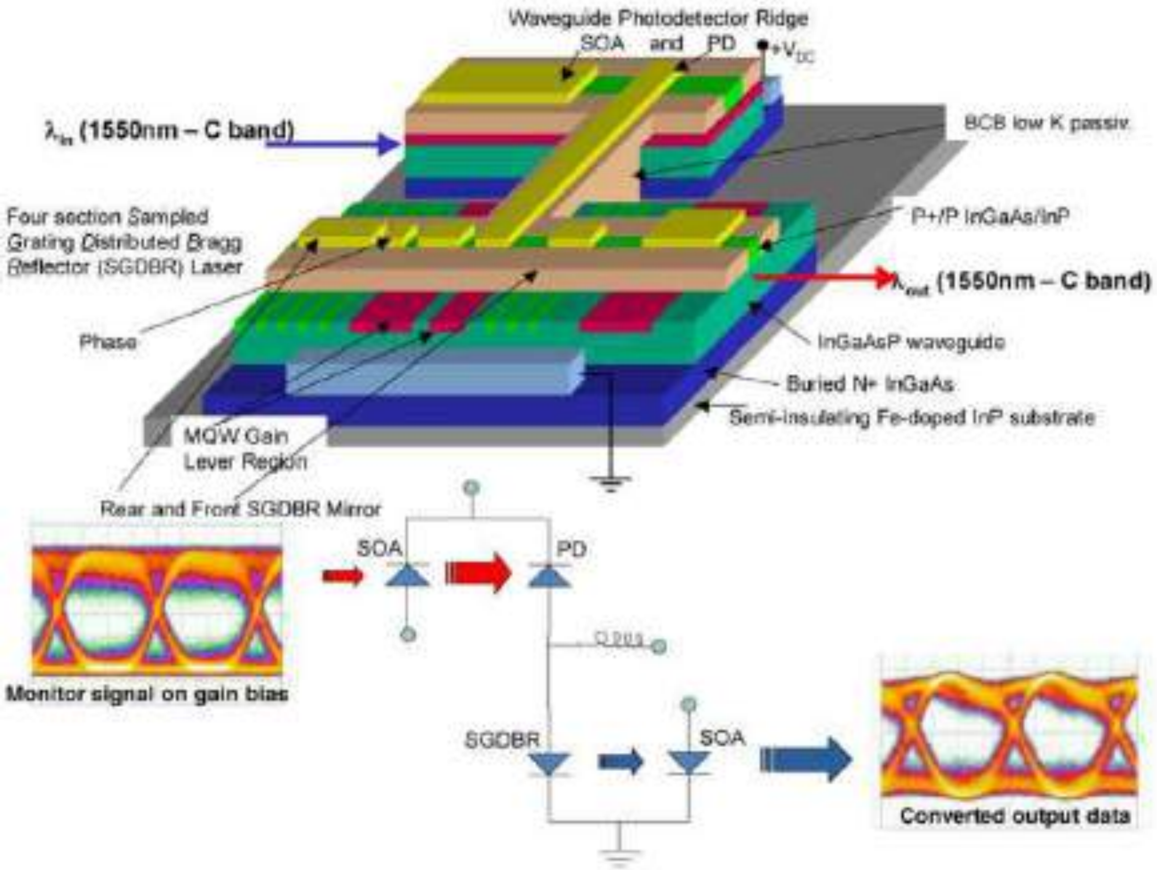


Fig. 17. Directly-driven SOA-PD/SGDBR-SOA wavelength converter. Schematic and equivalent circuit, including eye patterns from input and output data at 2.5 Gb/s [49].

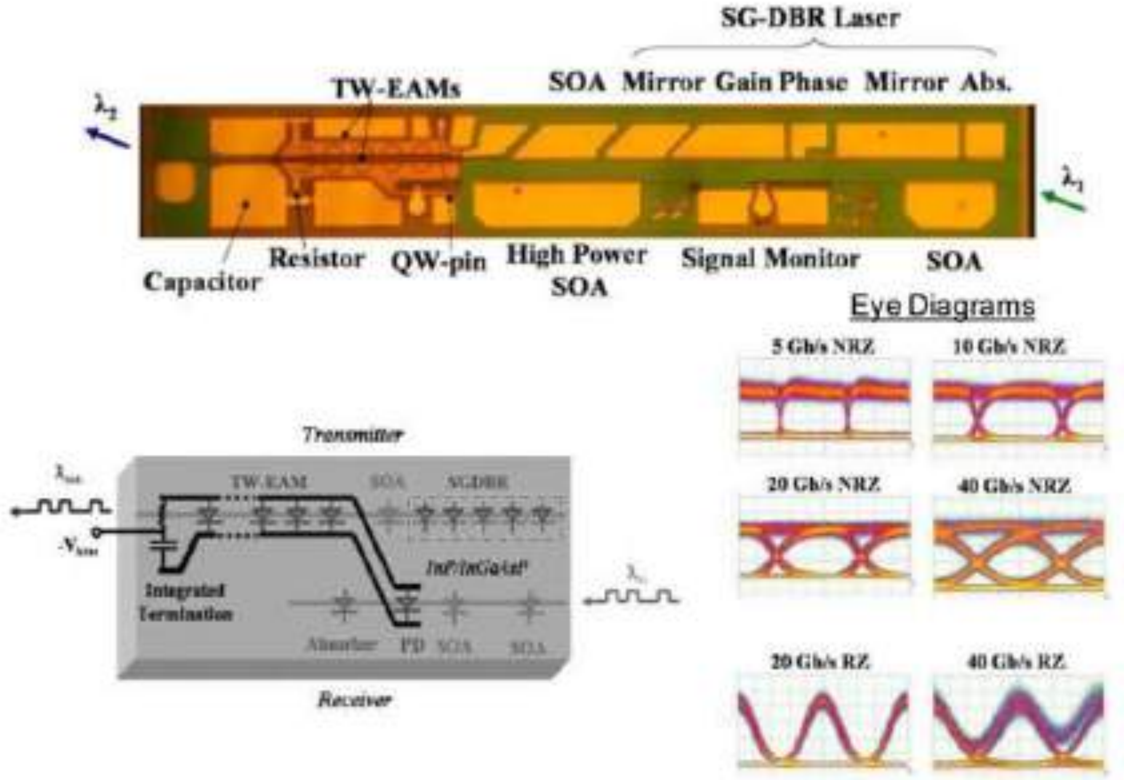
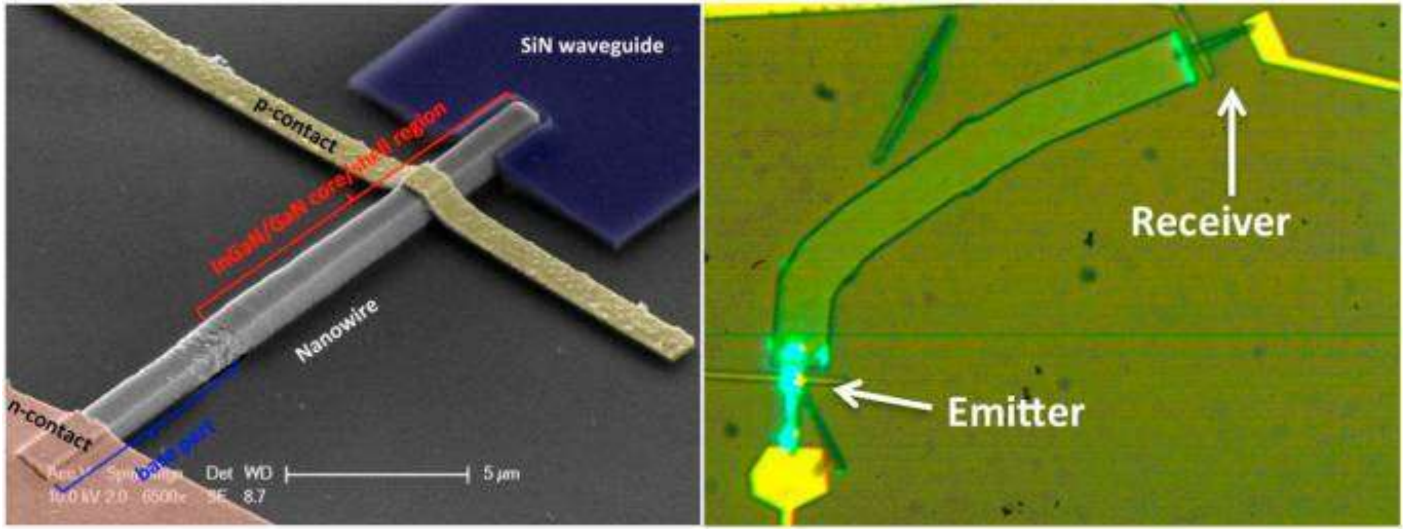
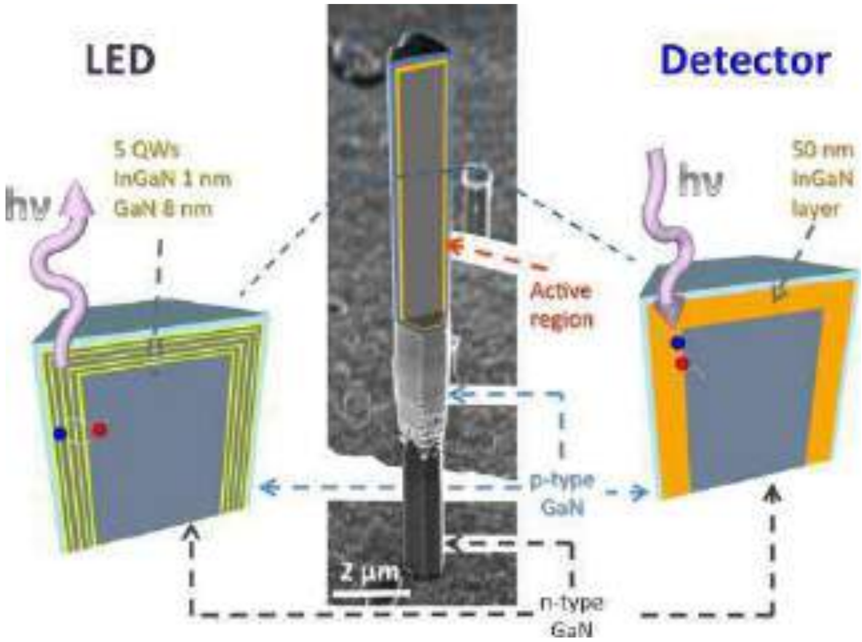


Fig. 19. Widely tunable, traveling-wave PD-EAM wavelength converter transparent to data format and bit rate. Photo, equivalent circuit, and eye diagrams from 5 to 40 Gb/s [12].

Larry A. Coldren et,al. Journal of Lightwave Technology, 2011

Combining InGaN/GaN Nanowire Emitters and Detectors

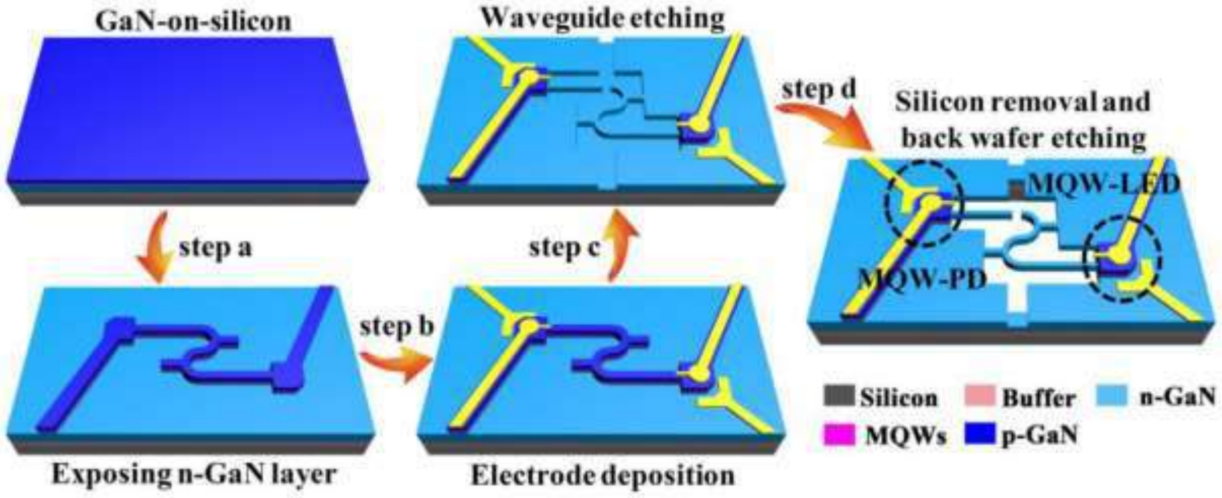


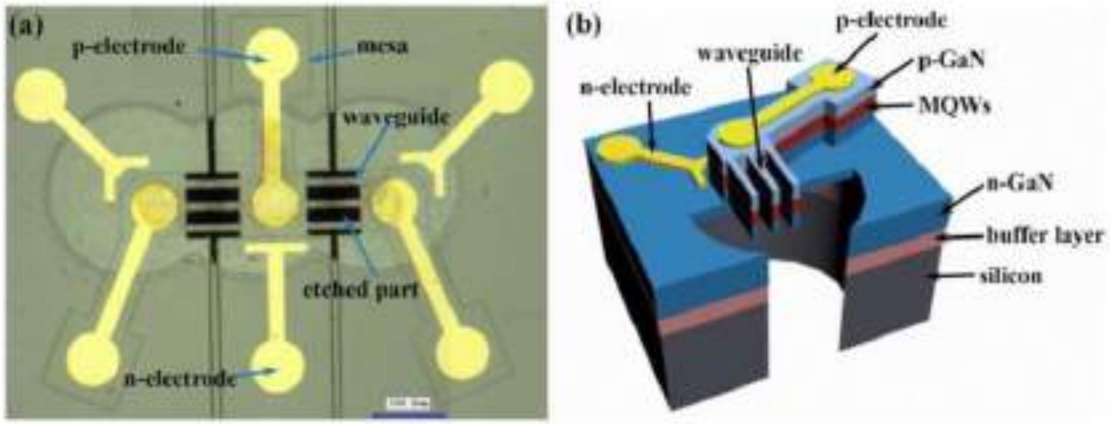


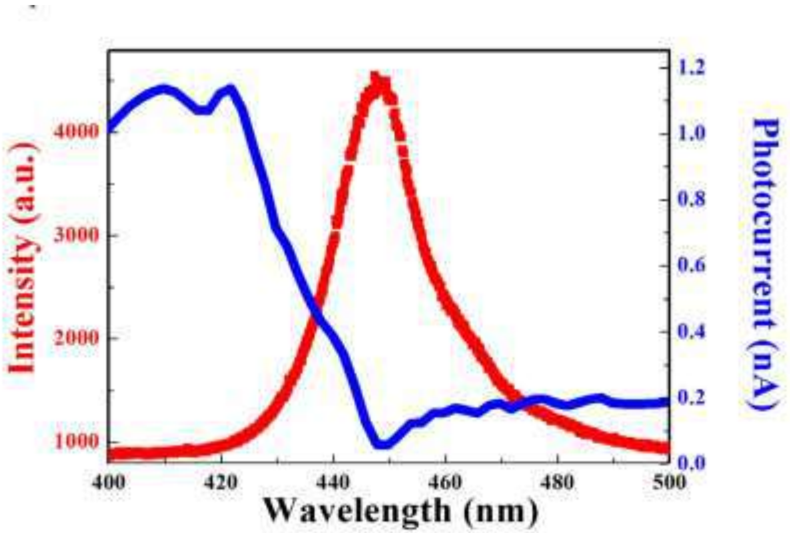
MOVPE-grown single wire InGaN/GaN p−n junction core−shell nanowires light-emitting diodes (LED) and photodetectors optically coupled by waveguides. The photodetector current trace shows signal variation correlated with the LED on/off switching with a fast transition time below 0.5 s.

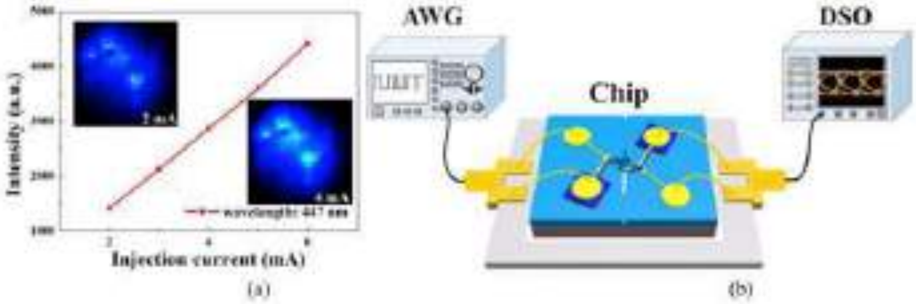
M. Tchernycheva et,al. CNRS, Nano Letters, 2014

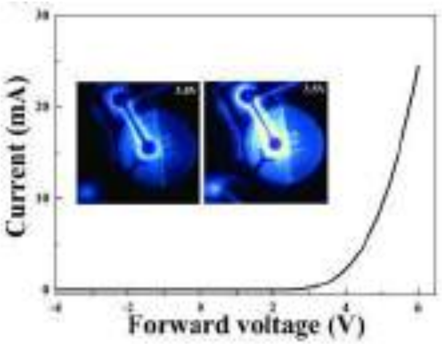
Integration of a LED with waveguide and receiver











Y. Wang, et,al. J Micromech Microeng, 2018
Y. Wang, et,al, Semiconductor Science and Technology, 2017
Y. Wang, et,al, IEEE Photonics Technology Letters, 2017
Y. Wang, et,al, Optics Express, 2016
Y. Wang, et,al, Applied Physics Letters, 2016
Y. Wang, et,al, Optical Materials Express, 2016

On-chip integration of GaN-based laser, modulator and PD

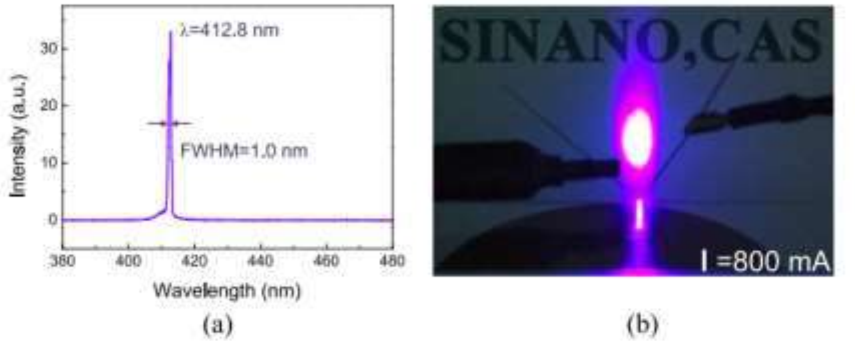


Fig. 2. (a) Lasing spectrum and (b) far-field pattern picture of the as-fabricated uncoated GaN-based LD grown on Si under $U_{\mathrm{Mod}} = +2$ V and $I_{\mathrm{Gain}} =$ 800 mA at room temperature.

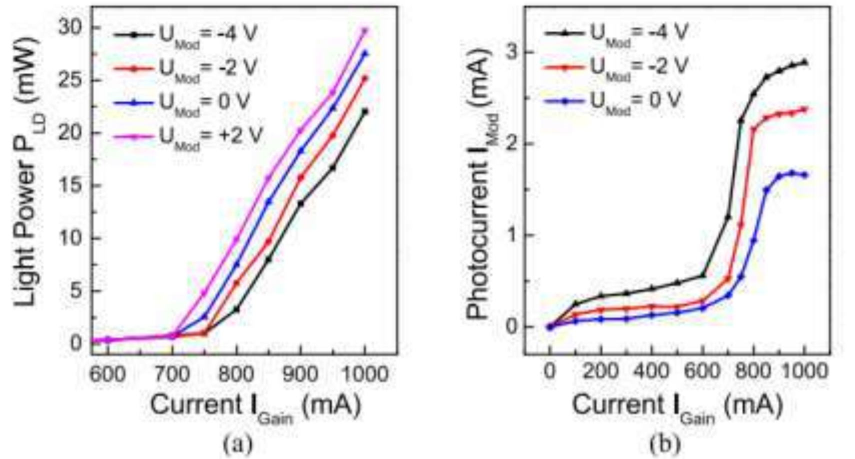


Fig. 3. (a) Output power of the LD (P_{LD}) and (b) photocurrent of the modulator section (I_{Mod}) as a function of the injection current in the gain section (I_{Gain}) under various modulator voltages (U_{Mod}).

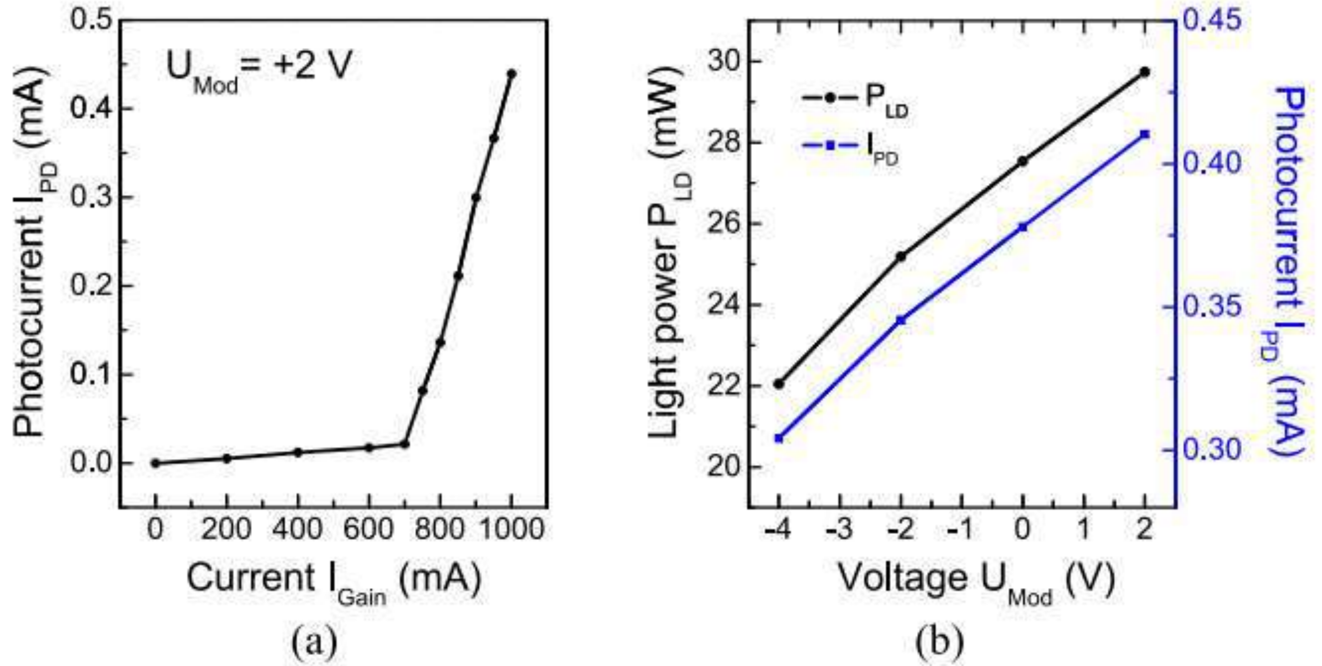
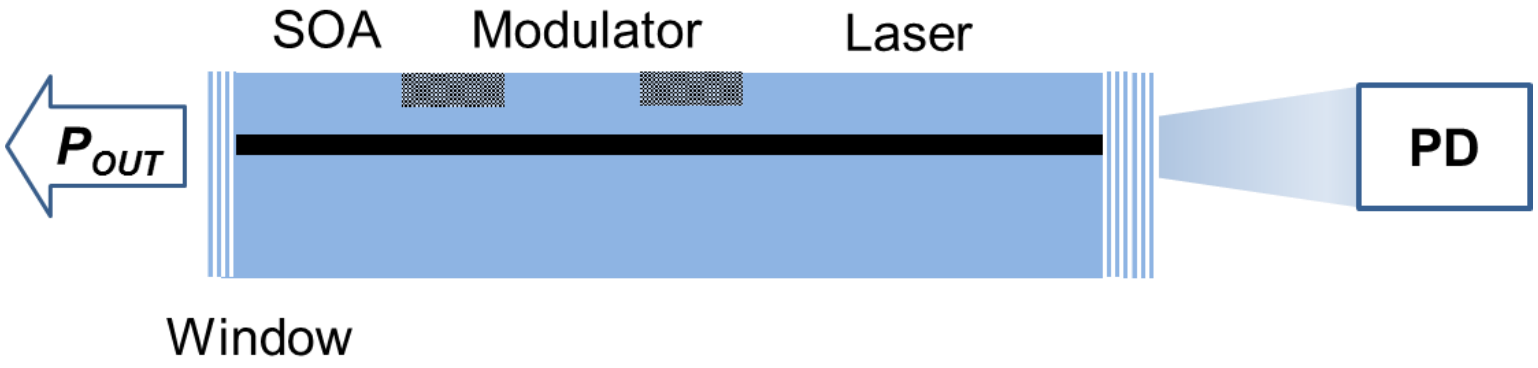


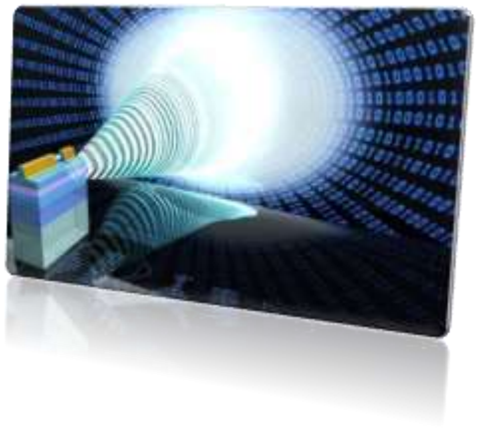
Fig. 4. (a) Photocurrent of the photodetector (I_{PD}) as a function of the injection current in the gain section (I_{Gain}) under $U_{\mathrm{Mod}} = +2$ V. (b) Output power of the LD (P_{LD}) and photocurrent of the photodetector (I_{PD}) as a function of the applied voltage to the modulator (U_{Mod}) at $I_{\mathrm{Gain}} = 1000$ mA.

M. Feng, et,al. IEEE Journal of Selected Topics in Quantum Electronics, 2018

III-Nitride laser based photonic integration

PIC at visible wavelength

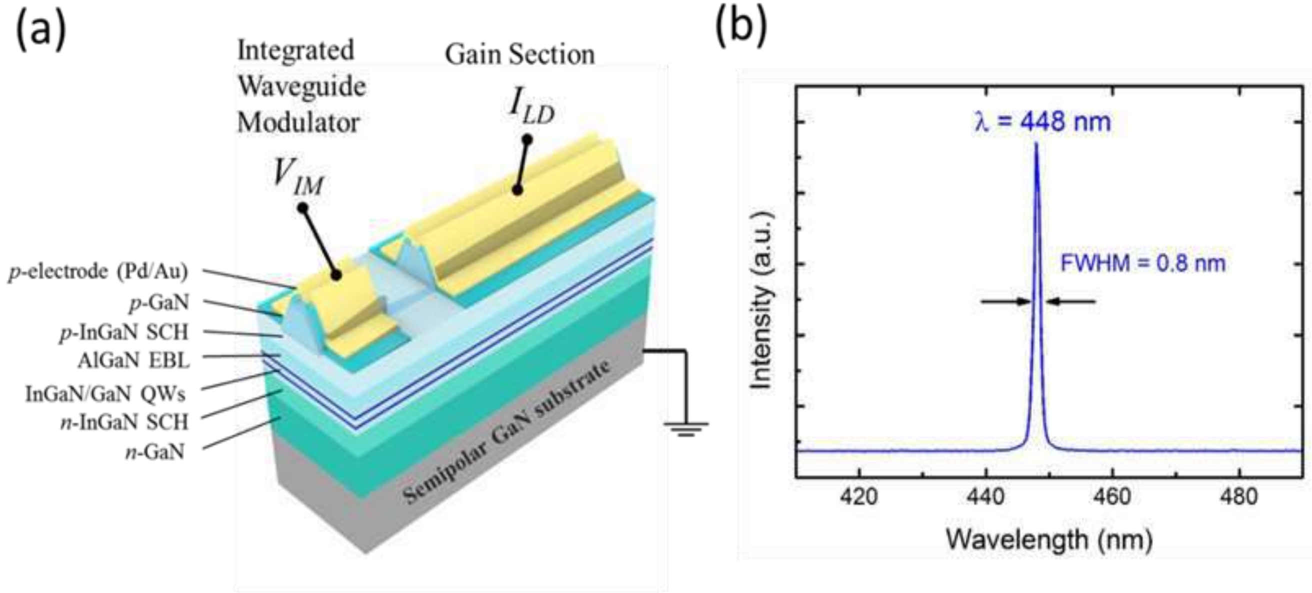


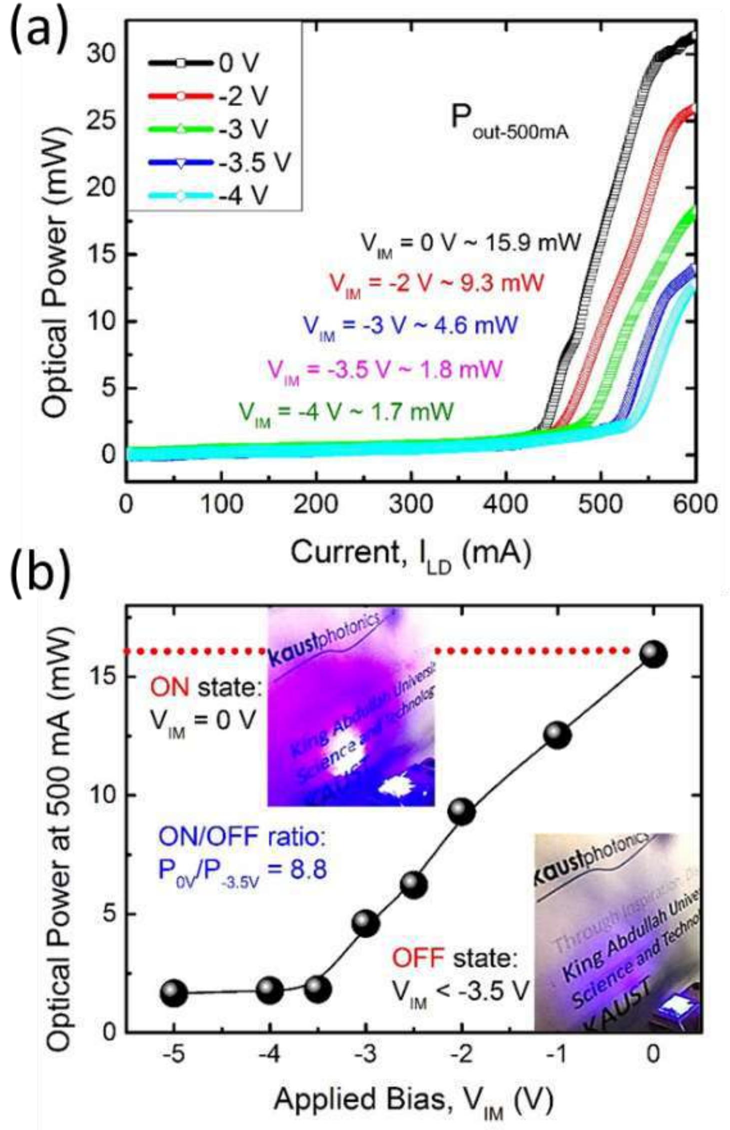


Monolithic integration of III-nitride photonic devices offers a novel solution for SSL-VLC applications with advantages:

- Compact, small form factor
- Low-cost (reduced epitaxial and fabrication expense)
- Multi-functionality

Integrated waveguide modulator-laser diode (IWM-LD)

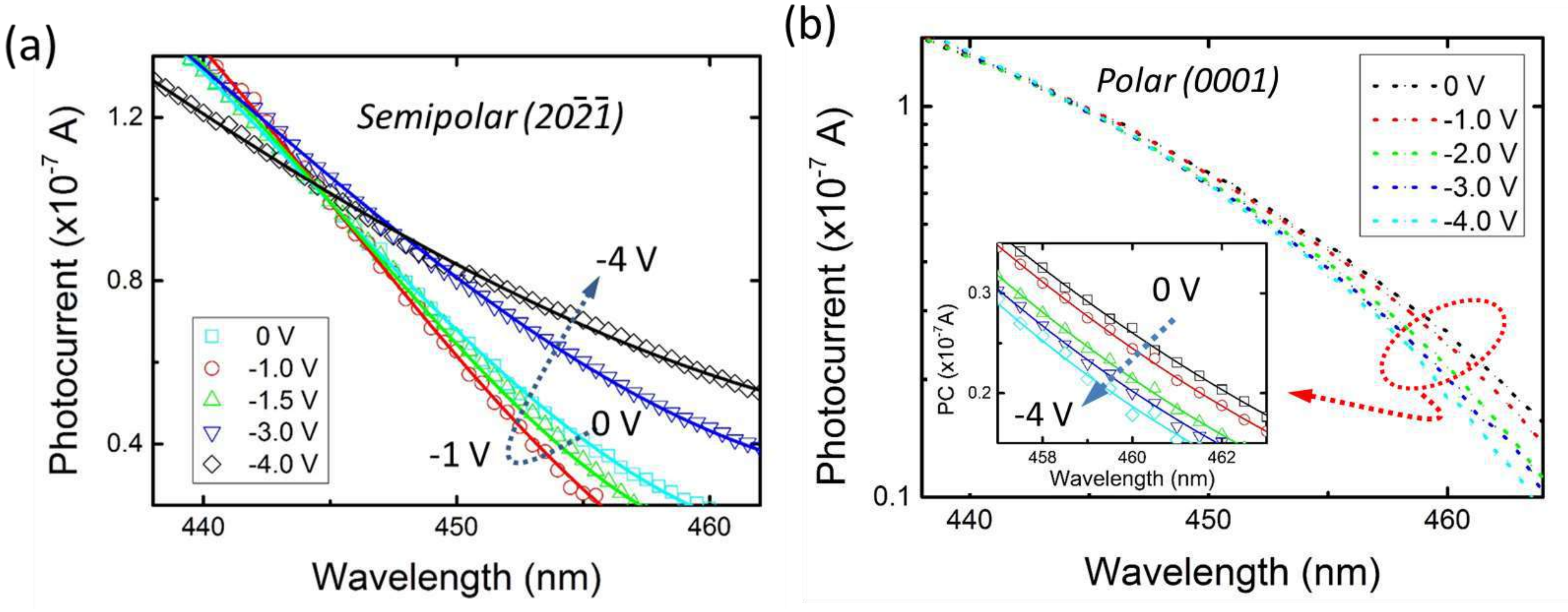




- IWM-LD at 448 nm.
- A large extinction ratio of 9.4 dB.
- A low operating voltage range of 3.5 V.
- A high modulation efficiency of 2.68 dB/V.

C. Shen, ACS Photonics, 2016
C. Shen, OECC, 2017
C. Shen, OMTA, 2020

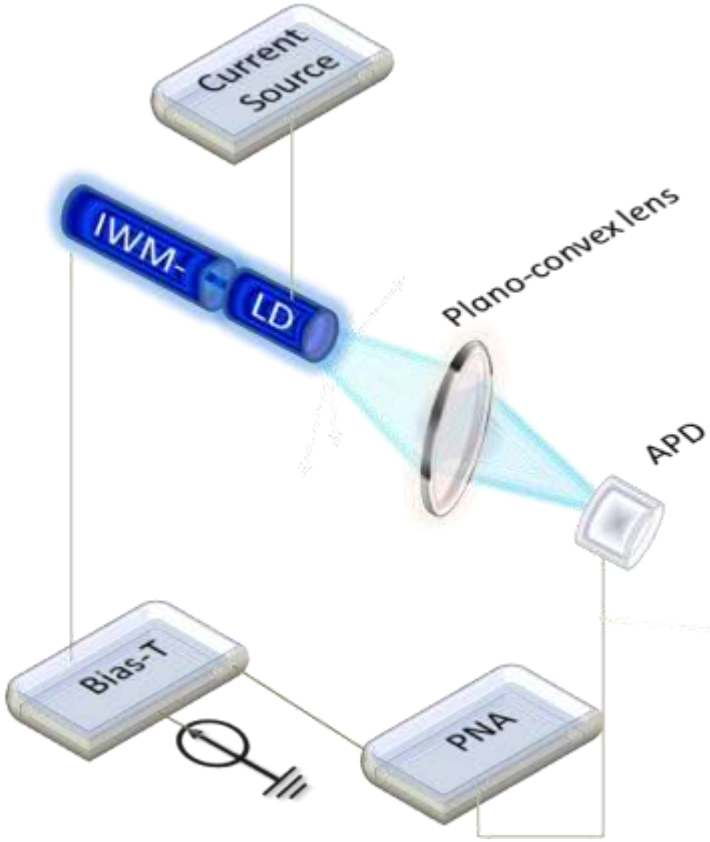
Integrated waveguide modulator-laser diode (IWM-LD)

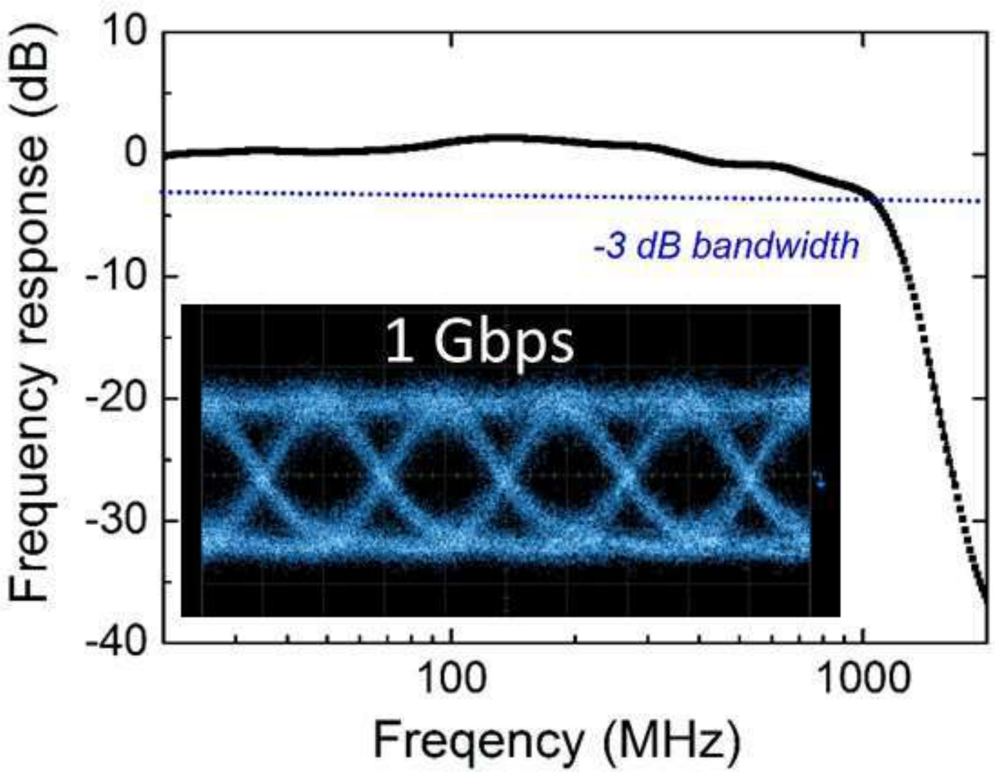


- ➢ The red-shifting clearly indicates the occurrence of an external bias-induced change in the absorption edge.
- ➢ Due to a reduced polarization field in semipolar QWs, the significant shifting of absorption edges in the IM region in response to modulation bias is effective in modulating the optical output power of the IWM-LD.

C. Shen, ACS Photonics, 2016
C. Shen, IPC, 2015

Integrated waveguide modulator-laser diode (IWM-LD)



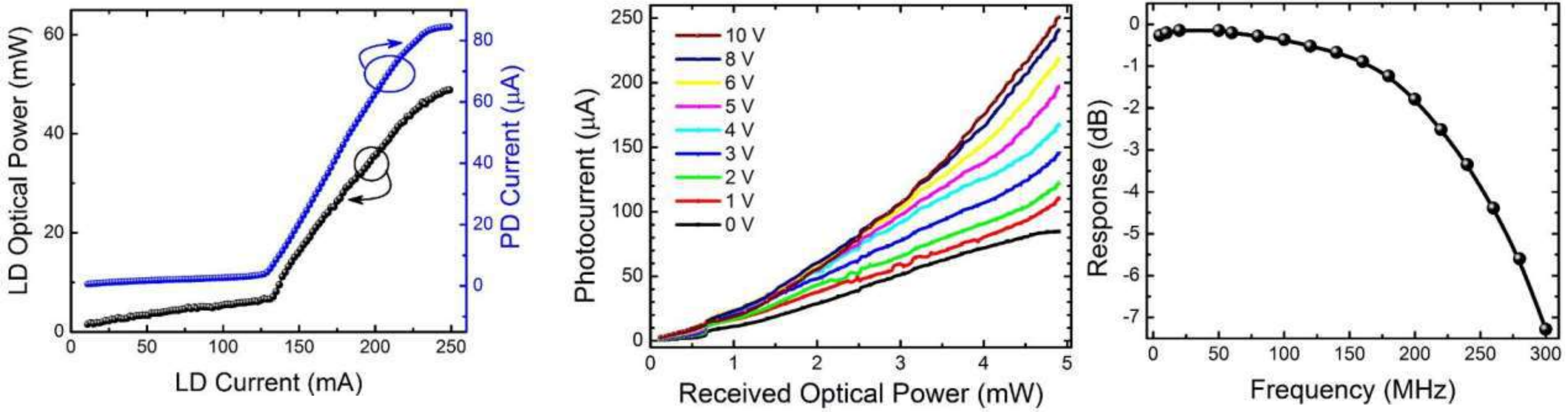


Data rate (Gbps)	Bit error rare (BER)
0.622	0.00
1	1.1×10^{-6}
1.5	2.1×10^{-5}
1.7	3.1×10^{-3}

- APD-limited BW of ~ 1GHz.
- A clear open eye at 1.7 Gbit/s using on-off keying (OOK) modulation scheme.

C. Shen, IEEE Photonics Conference, 2016

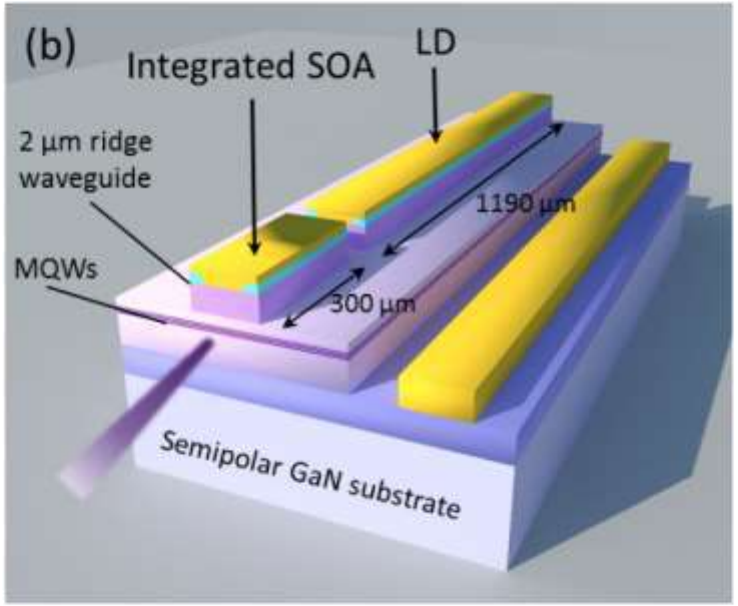
Integrated waveguide photodiode – laser diode (WPD-LD)

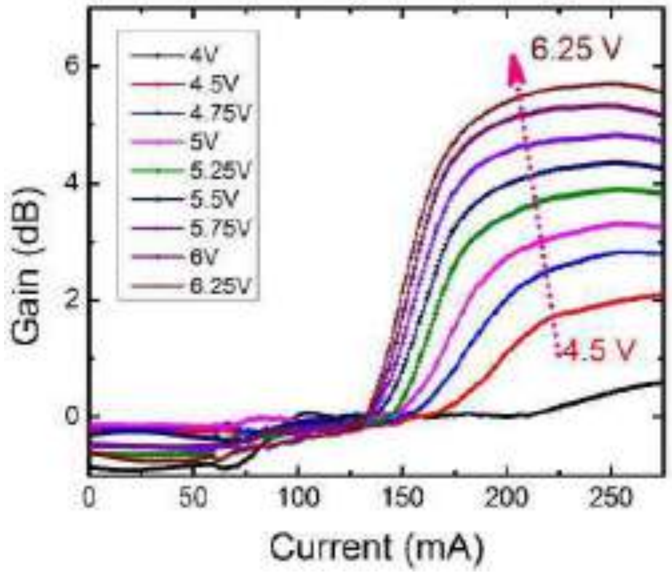


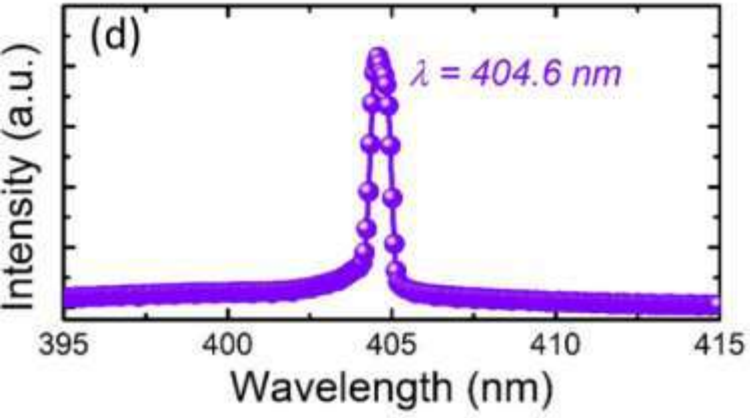
- Tx and Rx monolithic integration
- A 3-dB bandwidth of ~ 230 MHz is measured, suggesting a significantly improved modulation performance than the reported GaN p-i-n PDs.

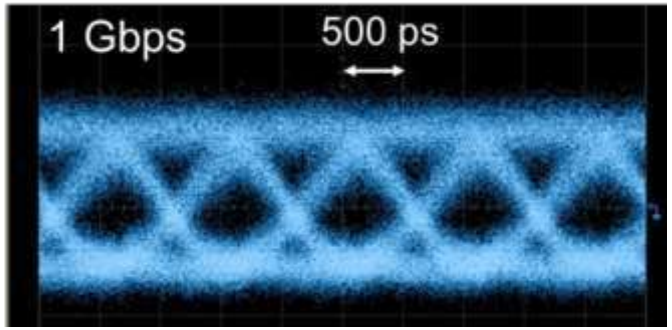
C. Shen, et,al. APEX, 2017
C. Shen, SPIE Photonics Asia, 2020

Integrated semiconductor optical amplifier – laser diode (SOA-LD)









<u>The first</u> InGaN/GaN SOA-LD

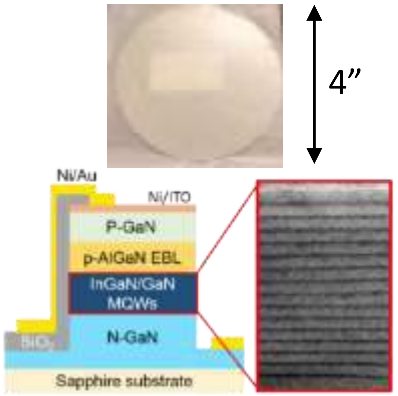
- Monolithic integration of SOA with LD at 405 nm.
- Optical gain and amplification ratio measured.
- The gain increase from 0.41 dB to 5.71 dB, when VSOA increases from 4 V to 6.25 V.
- Enable high-speed modulations for VLC applications.

C. Shen, et,al. IEDM, 2016
C. Shen, et,al. Opt. Express, 2017

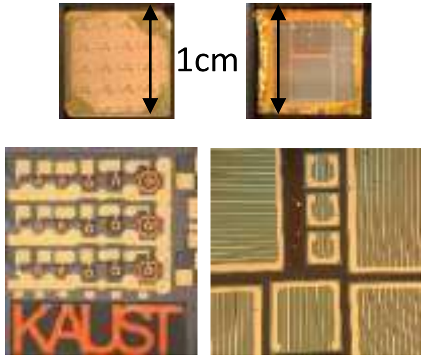
Outline

- Intro
- Transmitter Technology
- Photonics Integration
- **Receiver Technology**
- The end

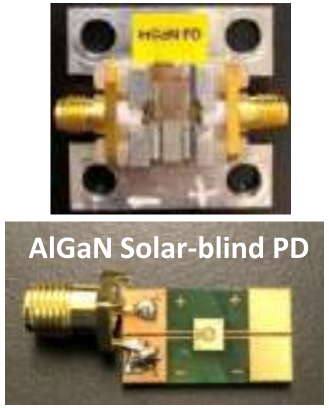
Receiver – III-nitride micro-photodetectors (μPD)



High-quality wafer



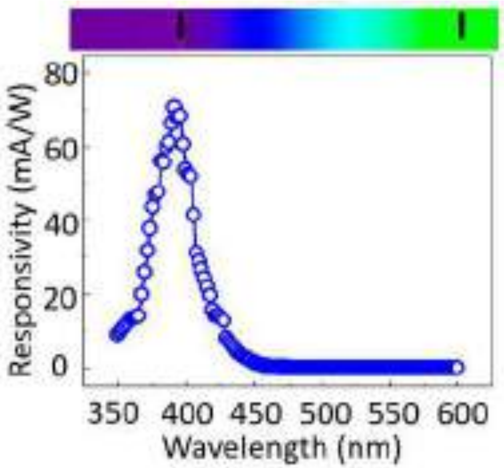
In-house fabricated PDs with various designs



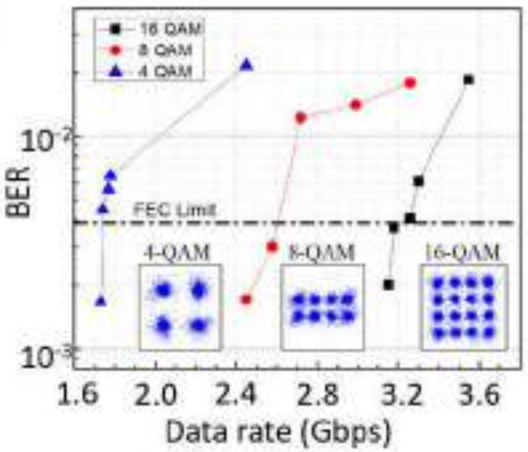
Different packages of photodetector chips

- **First demonstrations of InGaN-based micro-PD optical-receiver for fast VLC.**
- Similar devices can potentially offer switchable functions of **beam tracking, energy harvesting and parallel data transmission**.

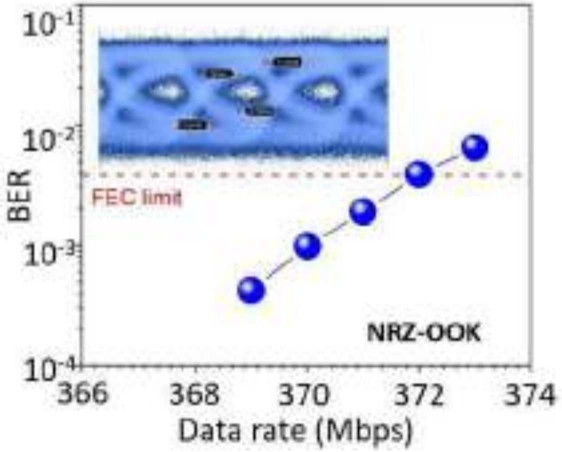
UV-violet light detection, High selectivity

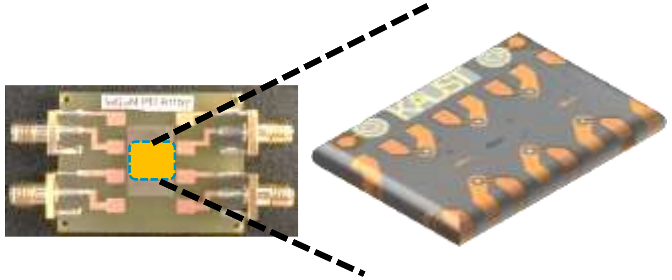


405-nm link



375-nm link over 1-m





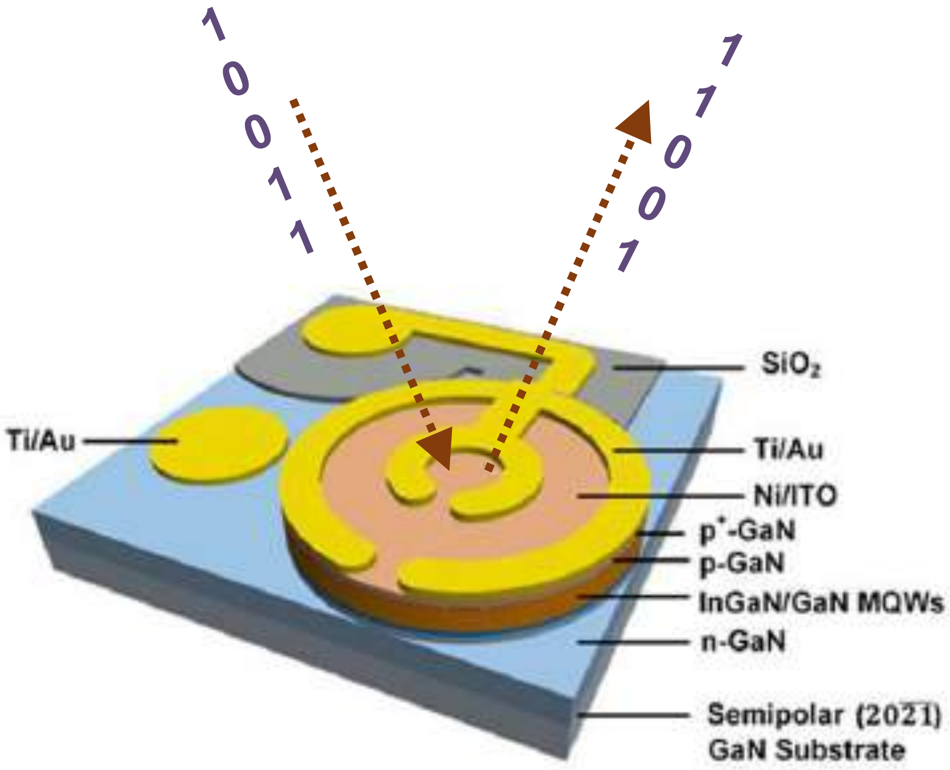
K-T. Ho et al., Optics Express, 26 (3), 2018

Wavelength-selective III-nitride micro-PD

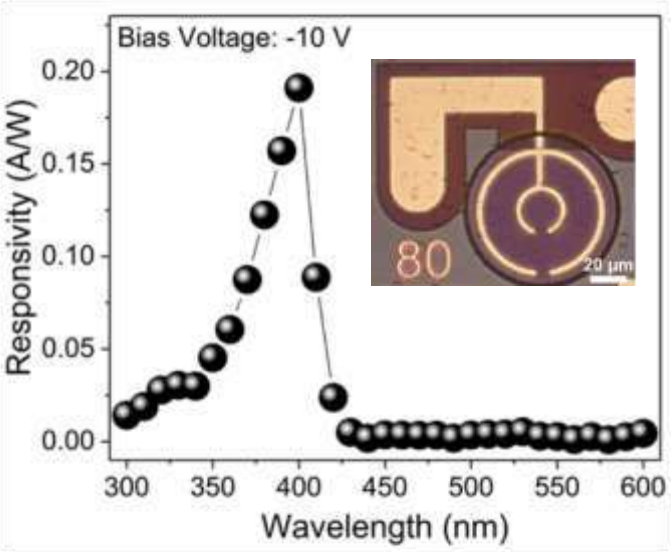
Non-return-to-zero on-off keying

(NRZ-OOK): 1.55 Gbit/s

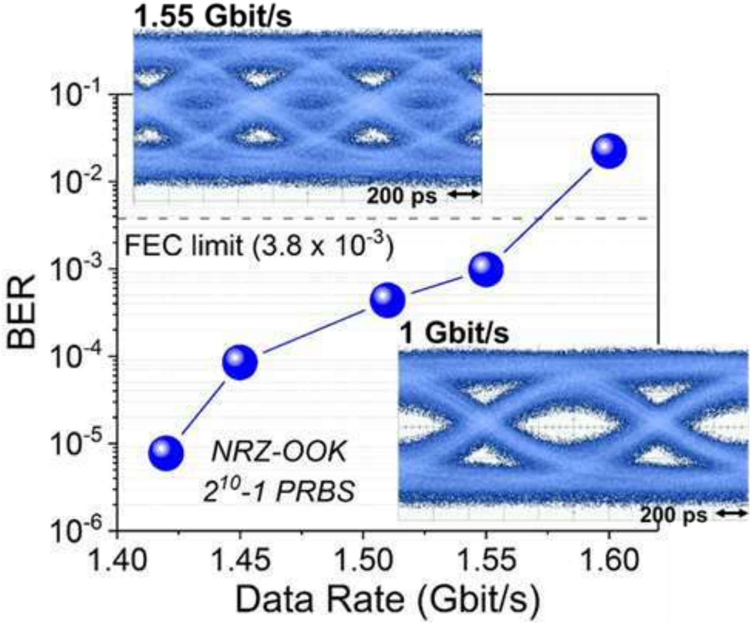
16-QAM-OFDM: 7.4 Gbit/s



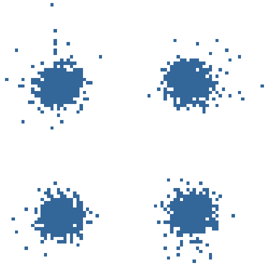
Spectral response



NRZ-OOK

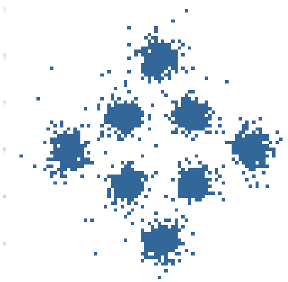


4-QAM-OFDM



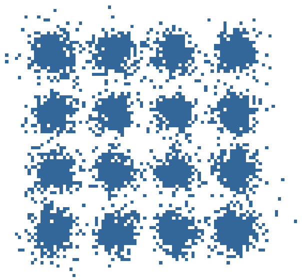
3 Gbit/s (Error-free)

8-QAM-OFDM



4.5 Gbit/s (BER: 1.5 × 10^{-3})

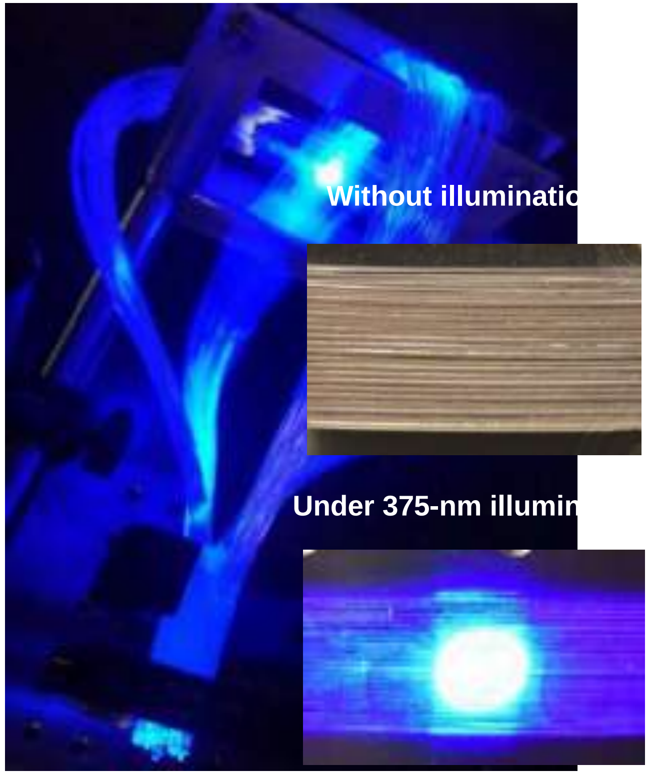
16-QAM-OFDM

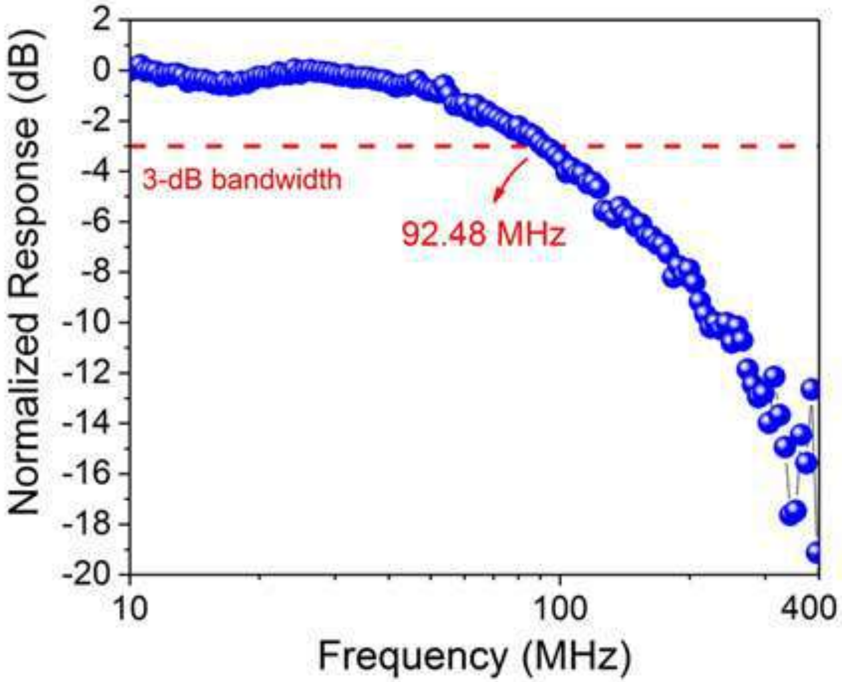


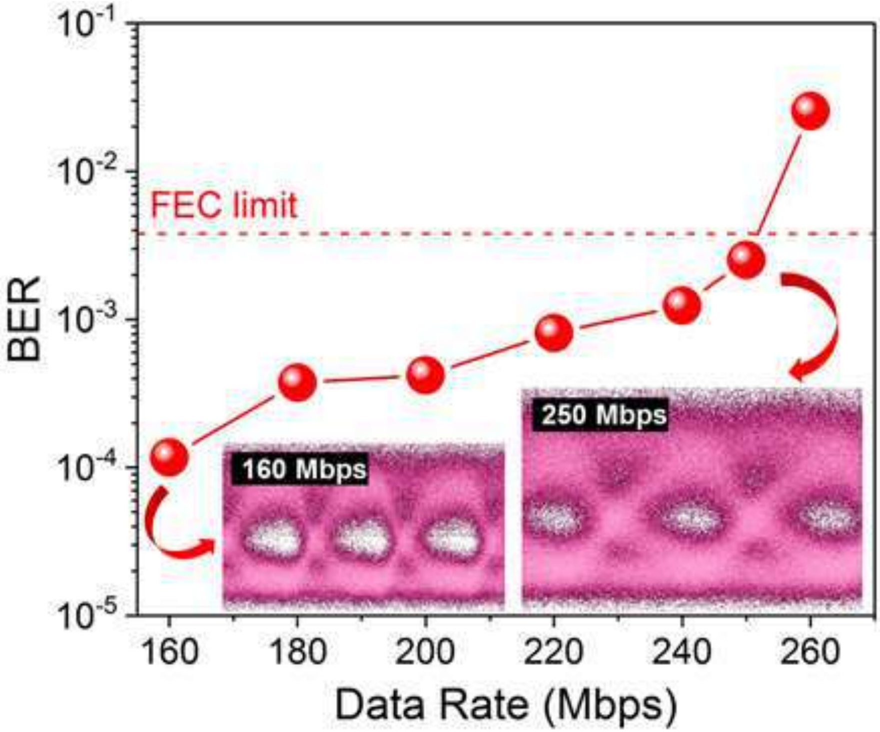
7.4 Gbit/s (BER: 3.4 × 10^{-3})

Optics Express, 26(3), 3037-3045 (2018)
Appl. Phys. Express 13, 0141001 (2020)
IEEE Photonics Tech. Lett. 32(13), 767 (2020)

Omnidirectional Optical-Antenna for High-speed UV Communication







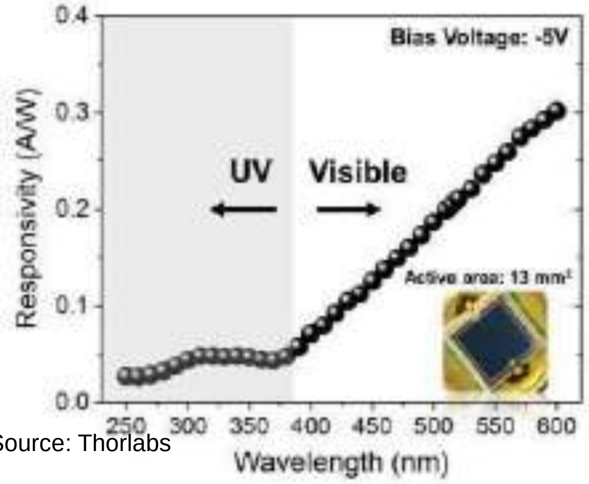
250 Mbit/s over 1.5-m water channel

- Ultra-large, flexible and omnidirectional detection
- Complement UV-based NLOS communication in UWOC
- Obviates the costly development path for large-bandgap semiconductors
- Flexible and high-bandwidth devices for high-speed UV-based photodetection

C.H. Kang, B. S. Ooi et al., Optics Express, 2019
C.H. Kang, B. S. Ooi et al., CLEO-Europe 2019
B. S. Ooi et al., USPTO 62/808,585

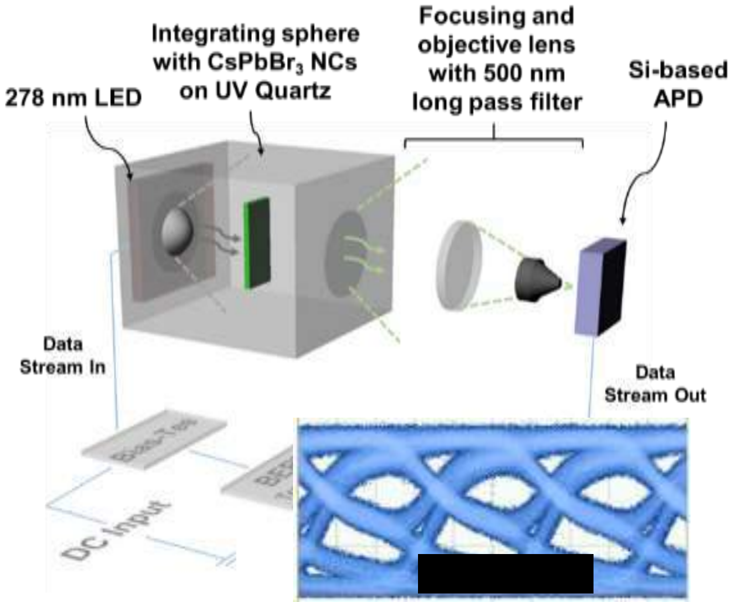
Receiver - Hybrid Perovskite-Silicon Solar-blind UVC Photoreceiver

Technology Gap:
Low responsivity in UV wavelengths!
(<<0.1 A/W at solar blind region)

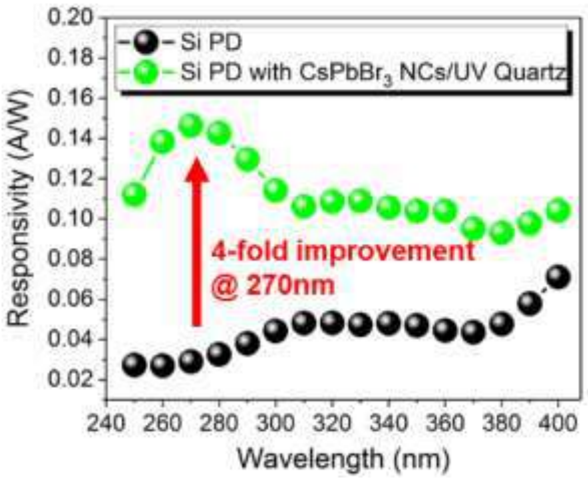


Source: Thorlabs

Our Solution



Enhanced responsivity



First demonstration of UVC communication using coated-Si-based platform at 34 Mbps

- 4-fold improvement in solar-blind detection
- Obviates costly III-nitride & III-oxide development path for UVC photodetector.

C.H. Kang, et al., Light: Science & Applications, 2019

Outline

- Intro
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Contemporary challenges and prospective solutions

Chanllenges and problems		Possible solutions
Bandwidth limitation of light sources	→	Super high-bandwidth light sources with new materials and new mechanisms
Si-based detectors are mainly sensitive to infrared waves	→	High responsivity detectors based on AlGaAs / single photon detectors
Lack of ASIC for VLC baseband processing	→	AFE including driver chips / TIA chips Digital chips for baseband processing
Point-to-point communication based on single transmitter and detector	→	MIMO communication based on transmitter and detector Arrays
Transmitting and receiving antennas require large lens groups	→	Fresnel lens, beam forming and steering based on nano optical antennas

N. Chi et,al. IEEE Vehicular Technology Magazine, 2020

References

1. "*Demonstration of a Low-Complexity Memory-Polynomial-aided Neural Network Equalizer for CAP Visible-Light Communication with Superluminescent Diode*", Opto-Electronic Advances 3, 200009 (2020)
2. "*Blue laser diode system with an enhanced wavelength tuning range*", IEEE Photonics Journal, 12(2) 1502110 (2020)
3. "*Non-line-of-sight methodology for high-speed wireless optical communication in highly turbid water*", Optics Communications, 461, 125264 (2020)
4. "*Toward reliable and energy-efficient visible light communication using amorphous silicon thin-film solar cells*", Optics Express, 27(24), 34542-34551 (2019)
5. "*Ultraviolet-to-blue color-converting scintillating-fibers photoreceiver for 375-nm laser-based underwater wireless optical communication*", Optics Express, 27(21), 30450-30461 (2019).
6. "*On the realization of across wavy water-air-interface diffuse-line-of-sight communication based on an ultraviolet emitter*", Optics Express, 27(14), 19635-19649 (2019).
7. "*Analysis of Optical Injection on Red and Blue Laser Diodes for High Bit-rate Visible Light Communication*", Optics Communications, 49, 79-85 (2019).
8. "*Group-III-nitride superluminescent diodes for solid-state lighting and high-speed visible light communications*", IEEE Journal of Selected Topics in Quantum Electronics, 25(6), 2000110, Nov.-Dec. 2019 (2019)
9. "A tutorial on laser-based lighting and visible light communications: device and technology", Chinese Optics Letters, 17(4), 040601 (2019) .

References

1. "*High-power blue superluminescent diode for high CRI lighting and high-speed visible light communication*", Optics Express 26(20), 26355-26364 (2018).
2. "*Investigation of self-injection locked visible laser diodes for high bit-rate visible light communication*", IEEE Photonics Journal. 10(4) 7905511 (2018)
3. "*Light based underwater wireless communications*", Japanese Journal of Applied Physics, 57(8S2), 08PA06 (2018)
   "*375-nm ultraviolet-laser based non-line-of-sight underwater optical communication*". Optics Express, 26(10), 12870-12877 (2018).
4. "*3.2 Gigabit-per-second Visible Light Communication Link with InGaN/GaN MQW Micro-Photodetector*". Optics Express, 26(3), 3037-3045 (2018).
5. "*Semipolar InGaN quantum-well laser diode with integrated amplifier for visible light communications*". Optics Express 26(6), A219-A226 (2018).
6. "*71-Mbit/s Ultraviolet-B LED Communication Link based on 8-QAM-OFDM Modulation*", Optics Express, 25(19), 23267-23274 (2017).
7. "*Gigabit-per-second white light-based visible light communication using near-ultraviolet laser diode and RGB phosphors*". Optics Express, 25(15), 17480-17487 (2017).
8. "*Gigabit-per-second white light-based visible light communication using near-ultraviolet laser diode and RGB phosphors*". Optics Express, 25(15), 17480-17487 (2017).

References

1. "*Semipolar III-nitride quantum well waveguide photodetector integrated with laser diode for on-chip photonic system*" Applied Physics Express, 10, 042201 (2017).
2. "*True Yellow Light-emitting Diodes as Phosphor for Tunable Color-Rendering Index Laser-based White Light*". ACS Photonics, 3(11), 2089–2095 (2016).
3. "*20-meter underwater wireless optical communication link with 1.5 Gbps data rate*", Optics Express, 24 (22), 25502-25509 (2016).
4. "*High-speed 405-nm superluminescent diode (SLD) with 807-MHz modulation bandwidth*", Optics Express, 24 (18), 20281-20286 (2016).
5. "*Carbon nanotube-graphene composite film as transparent conductive electrode for GaN-based light-emitting diodes*". Applied Physics Letters, 109, 081902 (2016).
6. "*Ultrabroad Linewidth Orange-emitting Nanowires LED for High CRI Laser-based White Lighting and GigaHertz Communications.",* Optics Express, 24 (17), 19228-19236 (2016).
7. "*Droop-Free, Reliable, and High-Power InGaN/GaN Nanowire Light-Emitting Diodes for Monolithic Metal-Optoelectronics*", Nano Letters, 16(7), 4616-4623 (2016)
8. "*Perovskite Nanocrystals as a Color Converter for Visible Light Communication*", ACS Photonics, 3(7), 1150-1156 (2016)
9. "*High brightness semipolar* $\left(20\overline{21}\right)$ *blue InGaN/GaN superluminescent diodes for droop-free solid-state lighting and visible-light communications"* Optics Letters, 41(11), 2608-2611 (2016).

References

1. "*High-modulation-efficiency, integrated waveguide modulator-laser diode at 448 nm*", ACS Photonics, 3 (2), pp 262–268 (2016).
2. "*Facile formation of high-quality InGaN/GaN quantum-disks-in-nanowires on bulk-metal substrates for high-power light emitters*", Nano Letters, 16 (2), pp 1056–1063 (2016).
3. "*2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting communication system*", Optics Express, 23(23), 29779-29787 (2015).
4. "*Achieving uniform carriers distribution in MBE grown compositionally graded InGaN multiple-quantum-well LEDs*" IEEE Photonics Journal, 7(3), 2300209 (2015).
5. "*Enabling area-selective potential-energy engineering in InGaN/GaN quantum wells by post-growth intermixing*". Optics Express, 23(6), 7991-7998 (2015).
6. "*High-speed visible laser light communication: devices, systems and applications*", Proc. SPIE, 1171109, invited paper at SPIE Photonics West (2021).
7. "*Blue Superluminescent Diodes with GHz Bandwidth Exciting Perovskite Nanocrystals for High CRI White Lighting and High-Speed VLC*", CLEO: Science and Innovations, SM3N. 4 (2019).
8. "*Laser-based visible light communications and underwater wireless optical communications: a device perspective*", Proc. SPIE, 10939-13, SPIE Photonics West (2019).
9. "*Study on laser-based white light sources*", Proc. SPIE, 10940-52, presented at SPIE Photonics West (2019).
10. "*High power GaN-based blue superluminescent diode exceeding 450 mW*", IEEE International Semiconductor Laser Conference (ISLC 2018).

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谢谢!

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