IEEE Symposium on Computers and Communications (ISCC)
Sunday, July 9 16:30 - 17:30 (Africa/Tunis)
OWC Keynote: Visible light communication (VLC) for cars

Visible Light Communication (VLC) for Cars

Takaya Yamazato, Nagoya University
https://yamazato.nuee.nagoya-u.ac.jp/

1st Workshop on Optical Wireless Communications (OWC'23)
in association with
28th IEEE Symposium on Computers and Communications (ISCC 2023)
9-12 July 2023 // Tunis, Tunisia

WORKSHOP CO-CHAIRS

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Takaya Yamazato,
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University of Glasgow, UK

SCOPE AND MOTIVATION

Optical wireless communication (OWC) systems over terrestrial, space or underwater links are gaining much attention as cost-effective, sustainable and energy efficient candidates to meet the ever-increasing demand for capacity and quality for B5G/6G networks. Besides the compelling advantages of the high-power solid-state laser diodes for medium to long range applications, remarkable advances have been achieved in semiconductor sources such as light emitting diodes (LEDs) in visible light and ultraviolet wavelengths, multi-array light sources and detectors, tracking and steering. These advances provide huge potential for short/medium range wireless communication applications at low power and cost.

Despite the conspicuous advantages of OWC based systems, their design and

Visible Light Communication (VLC) for Cars

Special thanks to:
- **Dr. Chedlia Ben Naila, Nagoya University, Japan (OWC co-chair)**
- **Dr. Anna Maria Vegni, Roma Tre University, Italy (OWC co-chair)**
- **Dr. Hanaa Abumarshoud, University of Glasgow, UK (OWC co-chair)**
- **Dr. Habib M. Kammoun, University of Sfax, Tunisia (ISCC local organizing chair)**

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- **Suzuki Foundation**
- **Okawa Foundation of Information and Telecommunications**

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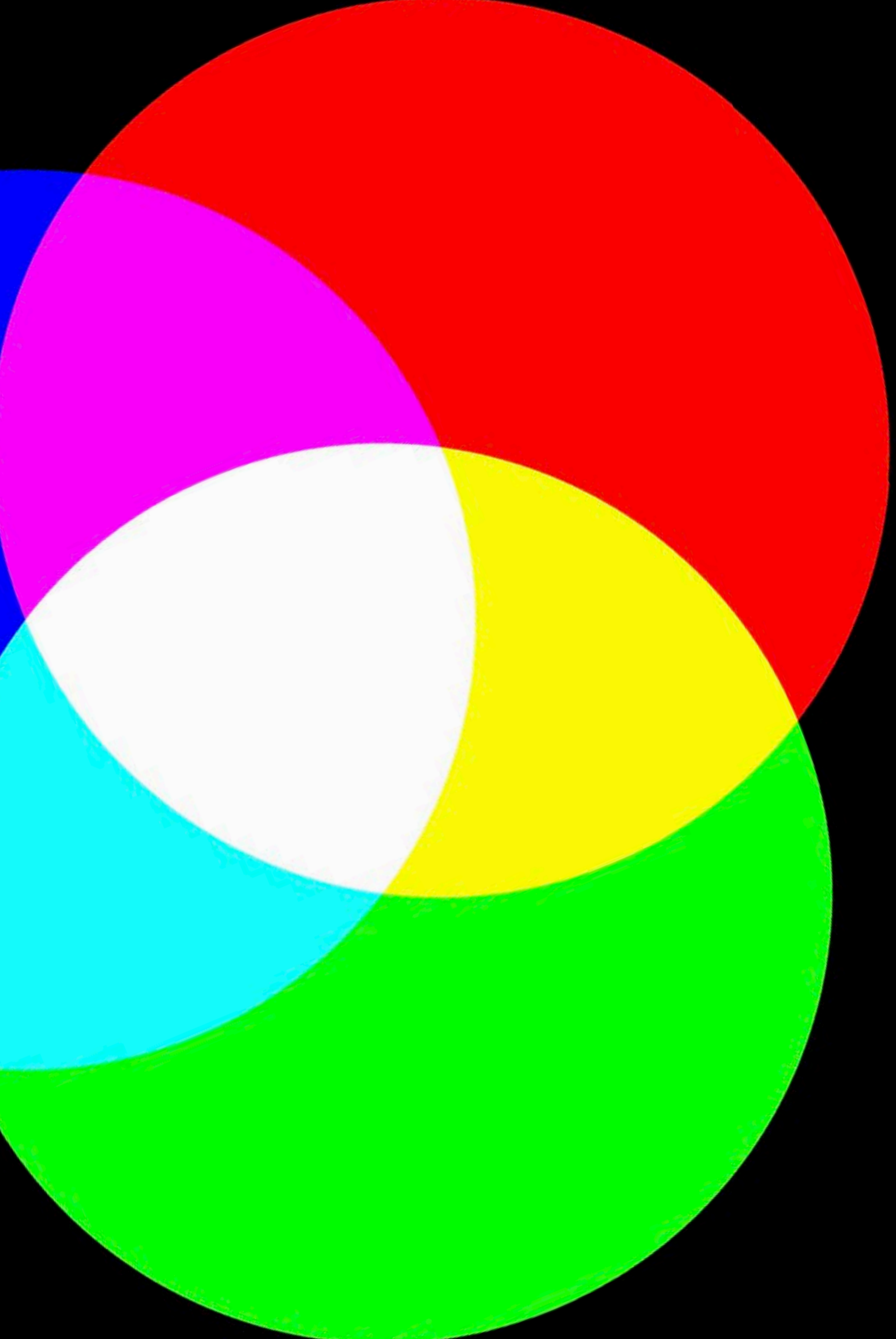
Visible light communications for Cars

- Brief history of LED and invention of blue LED
- Visible light communications (VLC), Image sensor communications (ISC)
- VLC using high-speed camera
- High-speed image processing for automotive applications
  - Vehicle to infrastructure visible light communication system
  - Range estimation using POC
  - ISC using rolling-shutter image sensor

Blue LED (innovation history)

"Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps."

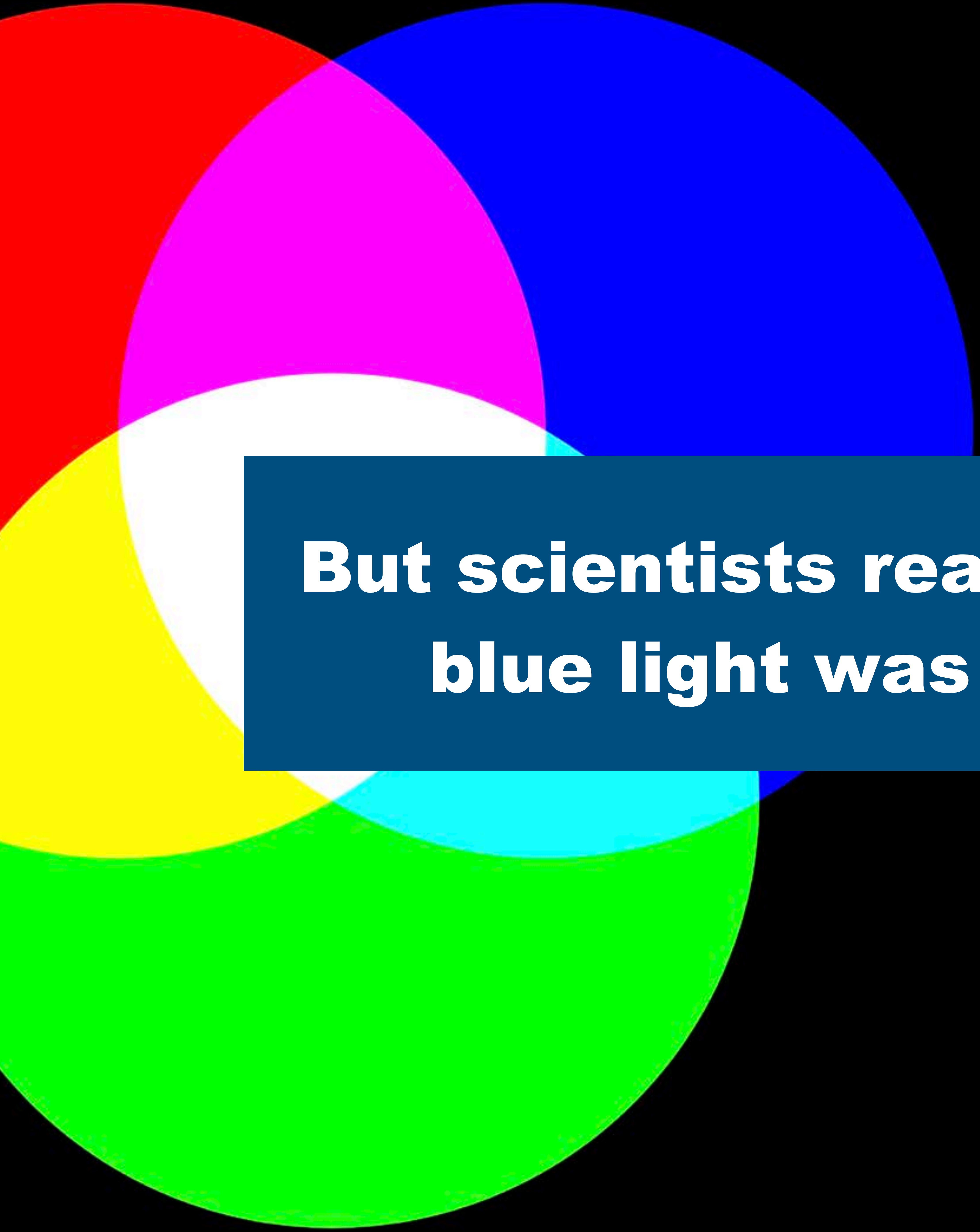


1961 Robert Biard and Gary Pittman (TI) invented an infra-red LED.

1962 Nick Holonyak, Jr. (GE) invented a visible red light LED.

1970s Scientists succeeded in making LEDs that emit a cyan (pale green) light.

1980s Ultra-bright magenda (orange-red), orange, green, and yellow LEDs were produced.



1961 Robert Biard and Gary Pittman (TI) invented an infra-red LED.

1962 Nick Holonyak, Jr. (GE) invented a visible red light LED.

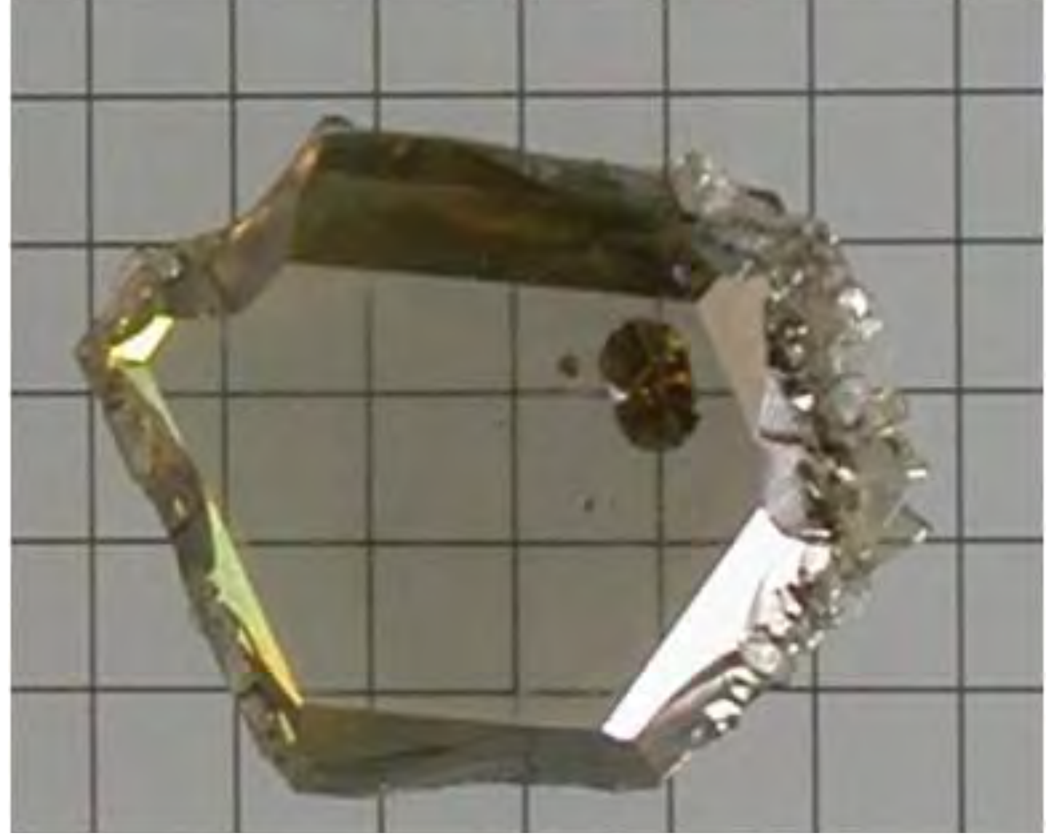
But scientists realized that the emission of blue light was considerably difficult.

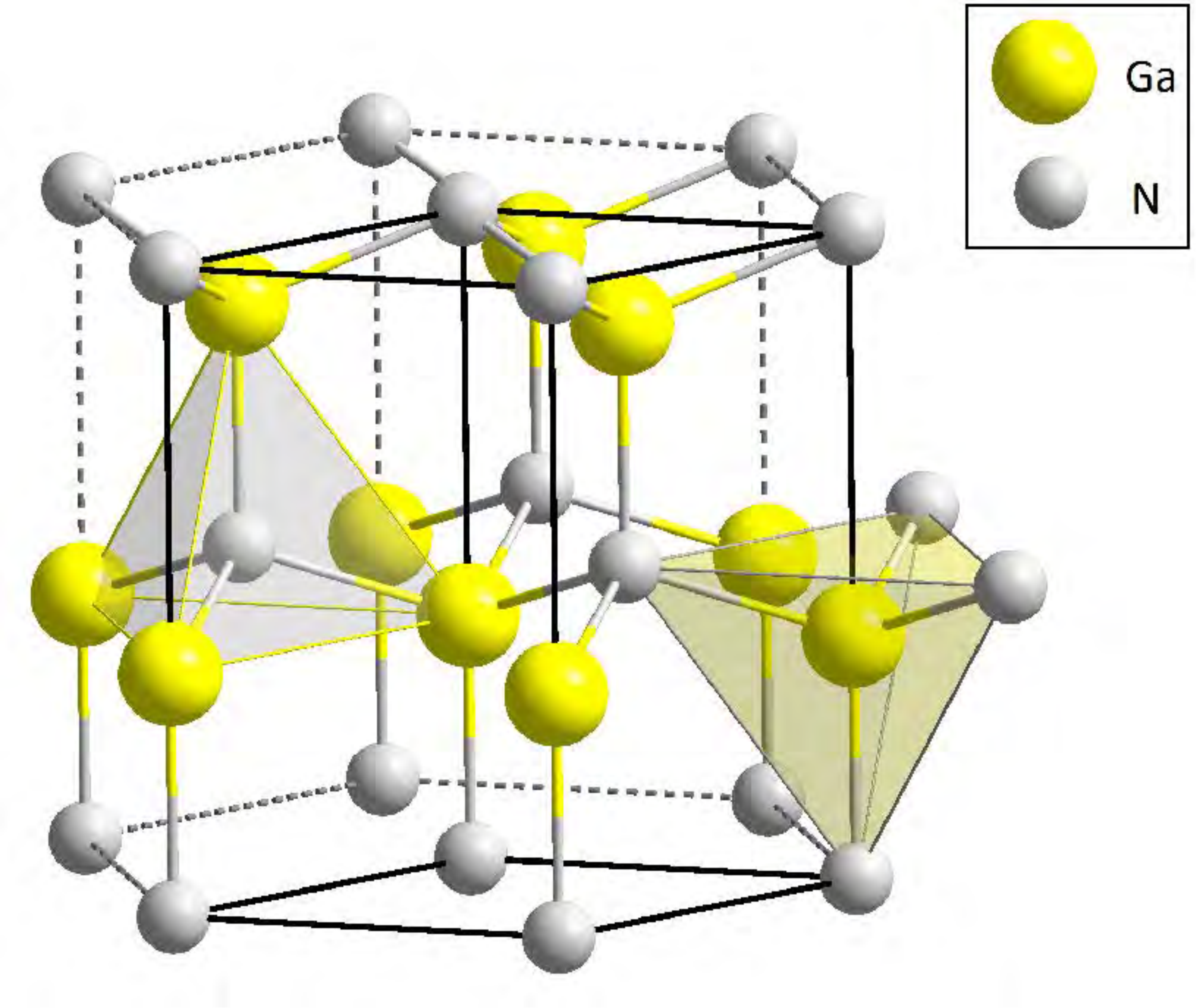
LEDs that emit a cyan (pale green) light.

1980s Ultra-bright magenda (orange-red), orange, green, and yellow LEDs were produced.

Gallium nitride (GaN)

- Gallium nitride was the material of choice.
- Material was considered appropriate, but practical difficulties had proved enormous.
- No one could grow gallium nitride crystals of high enough quality





https://en.wikipedia.org/wiki/Gallium_nitride

Dr. Isamu Akasaki

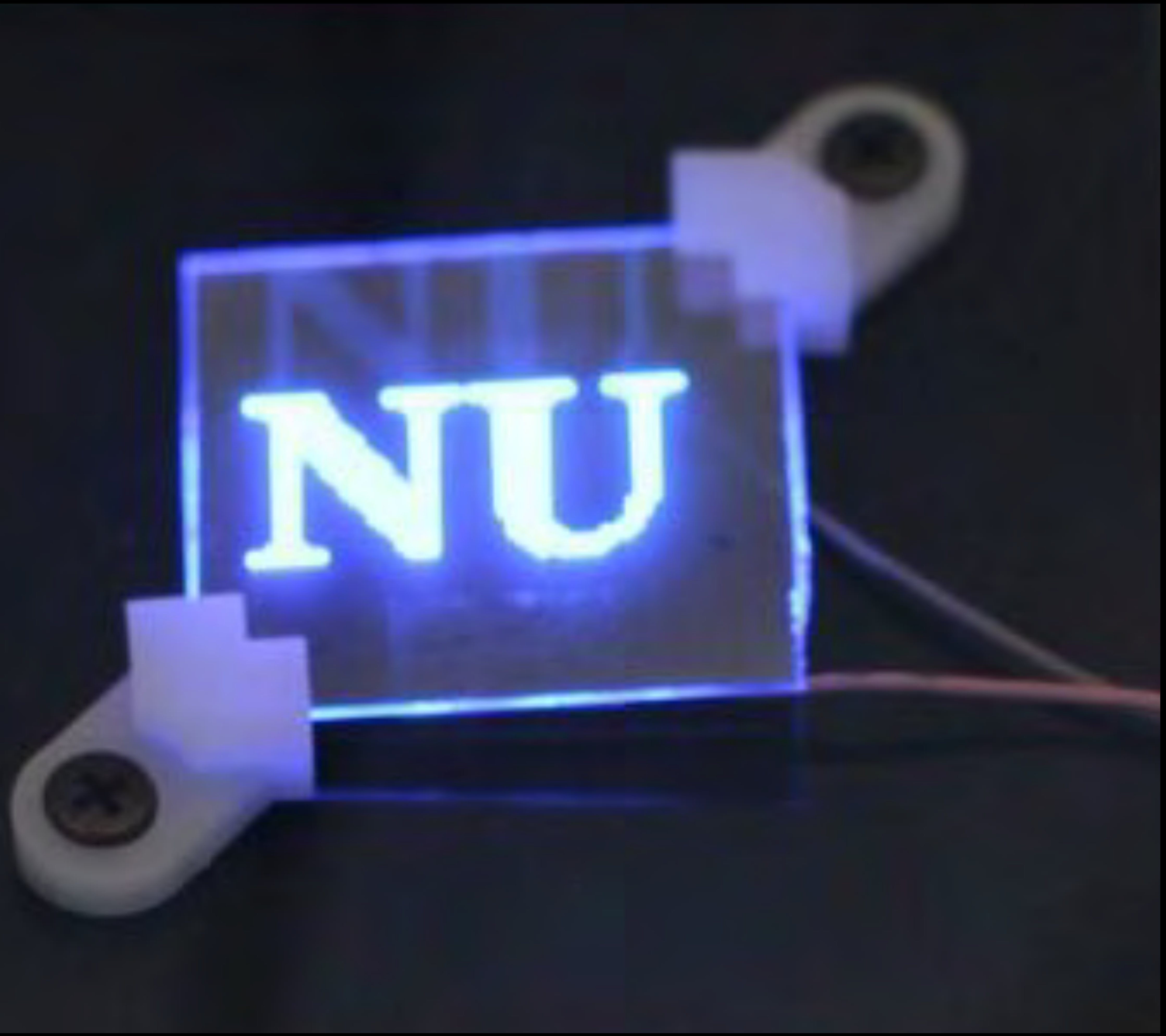
1952	Graduated from the School of Science, Kyoto University Began working at Kobe Kogyo Corporation
1959	Research Associate, School of Engineering, Nagoya University
1964	Lecturer, School of Engineering, Nagoya University
1964	Received Doctorate of Engineering, School of Engineering, Nagoya University
1981	Professor, School of Engineering, Nagoya University
1992	Retirement from Nagoya University Professor, Meijo University Professor Emeritus, Nagoya
2004	University Professor at Nagoya University

https://en.nagoya-u.ac.jp/people/nobel/isamu_akasaki/index.html (2021/9/16)

Dr. Hiroshi Amano

1960	Born in the city of Hamamatsu, Shizuoka Prefecture
1979	Graduated from Shizuoka Prefectural Hamamatsu Nishi Senior School
1983	Graduated from the School of Engineering, Nagoya University
1985	Completed Master's Course of the Graduate School of Engineering, Nagoya University
1988	Completed All But Dissertation (ABD) for a PhD degree of the Graduate School of Engineering, Nagoya University
1988	Research Associate, School of Engineering, Nagoya University
1989	Acquired the Doctor of Engineering, Nagoya University
1992	Assistant Professor, Faculty of Science and Technology, Meijo University
1998	Associate Professor, Faculty of Science and Technology, Meijo University
2002	Professor, Faculty of Science and Technology, Meijo University
2010	Professor, Graduate School of Engineering, Nagoya University

https://en.nagoya-u.ac.jp/people/nobel/hiroshi_amano/index.html (2021/9/16)



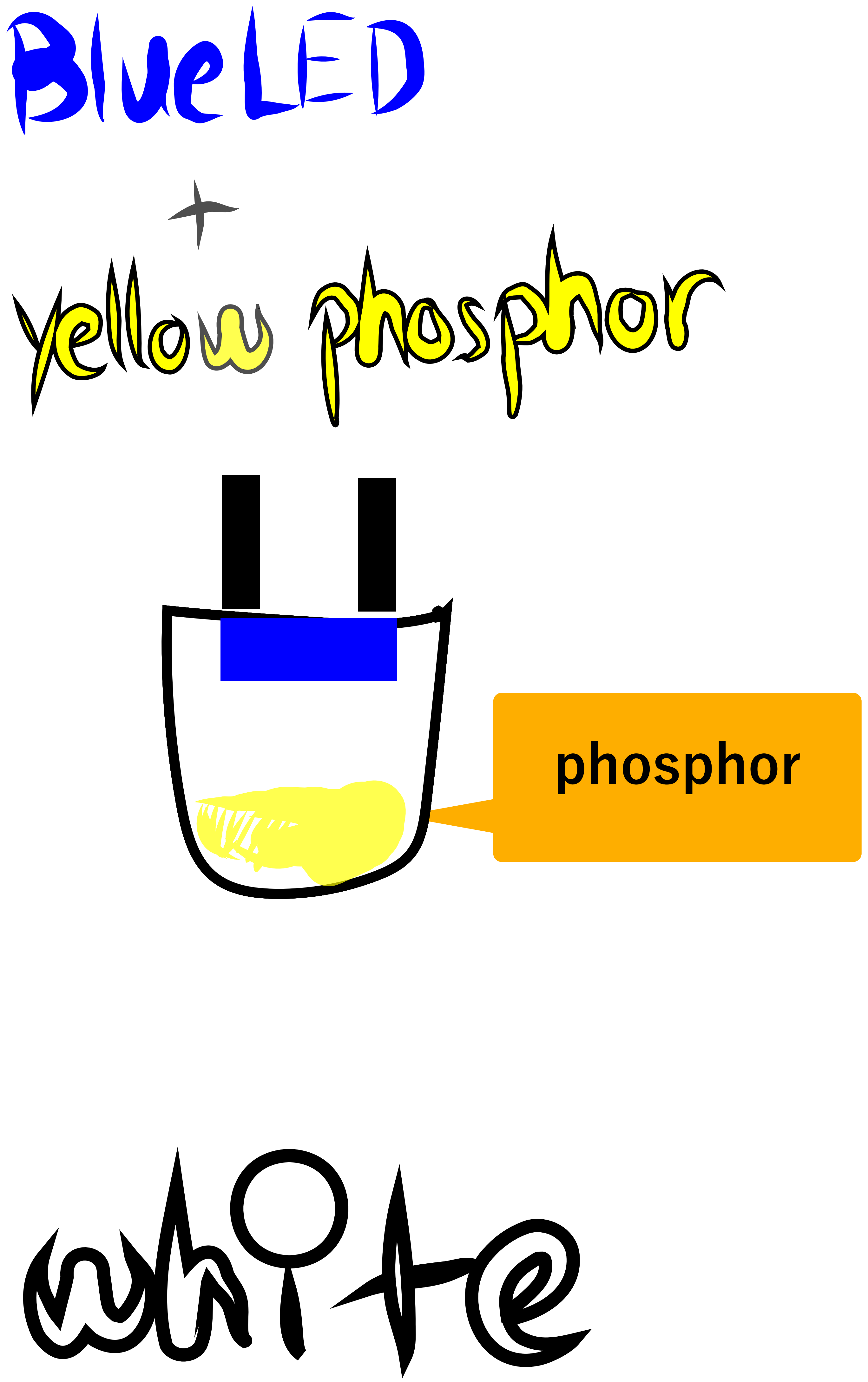
1986 Profs. Akasaki and Amano were the first to create a high-quality GaN crystal.

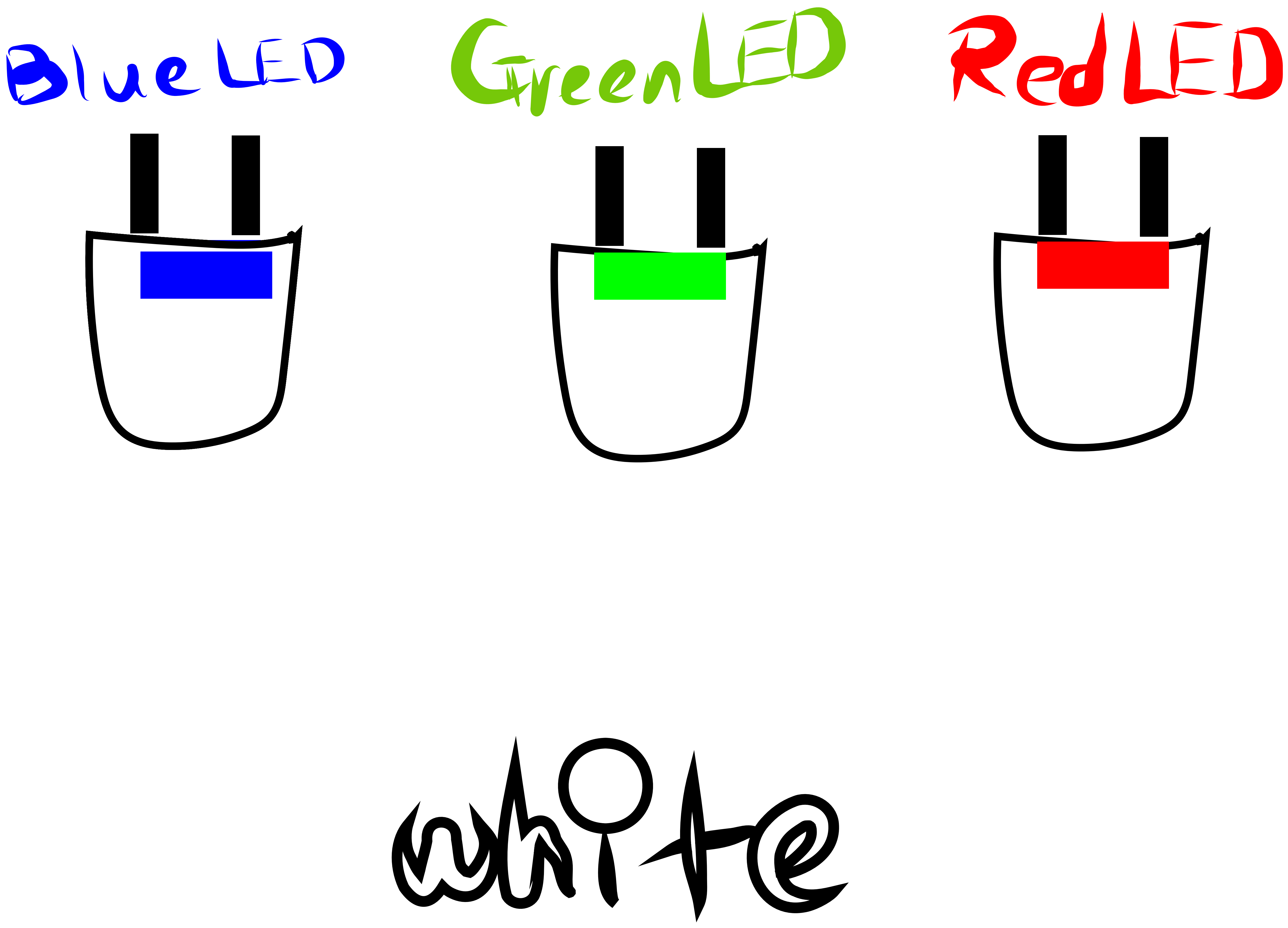
End of 1980s, they made a breakthrough in creating a p-type layer.

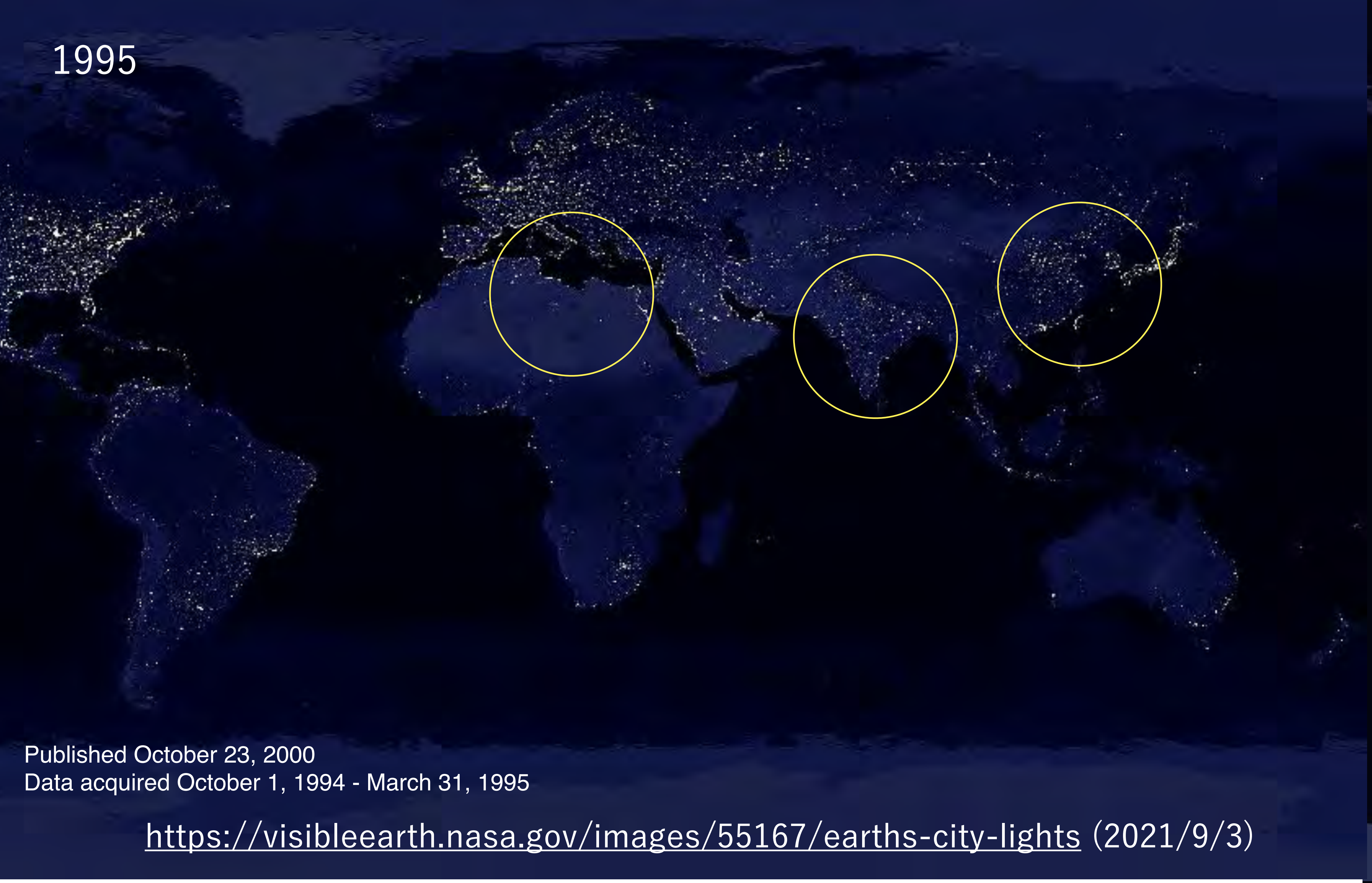
1992 Profs. Akasaki and Amano were able to present their first diode emitting a bright blue light.

Without a blue LED, there is no white light

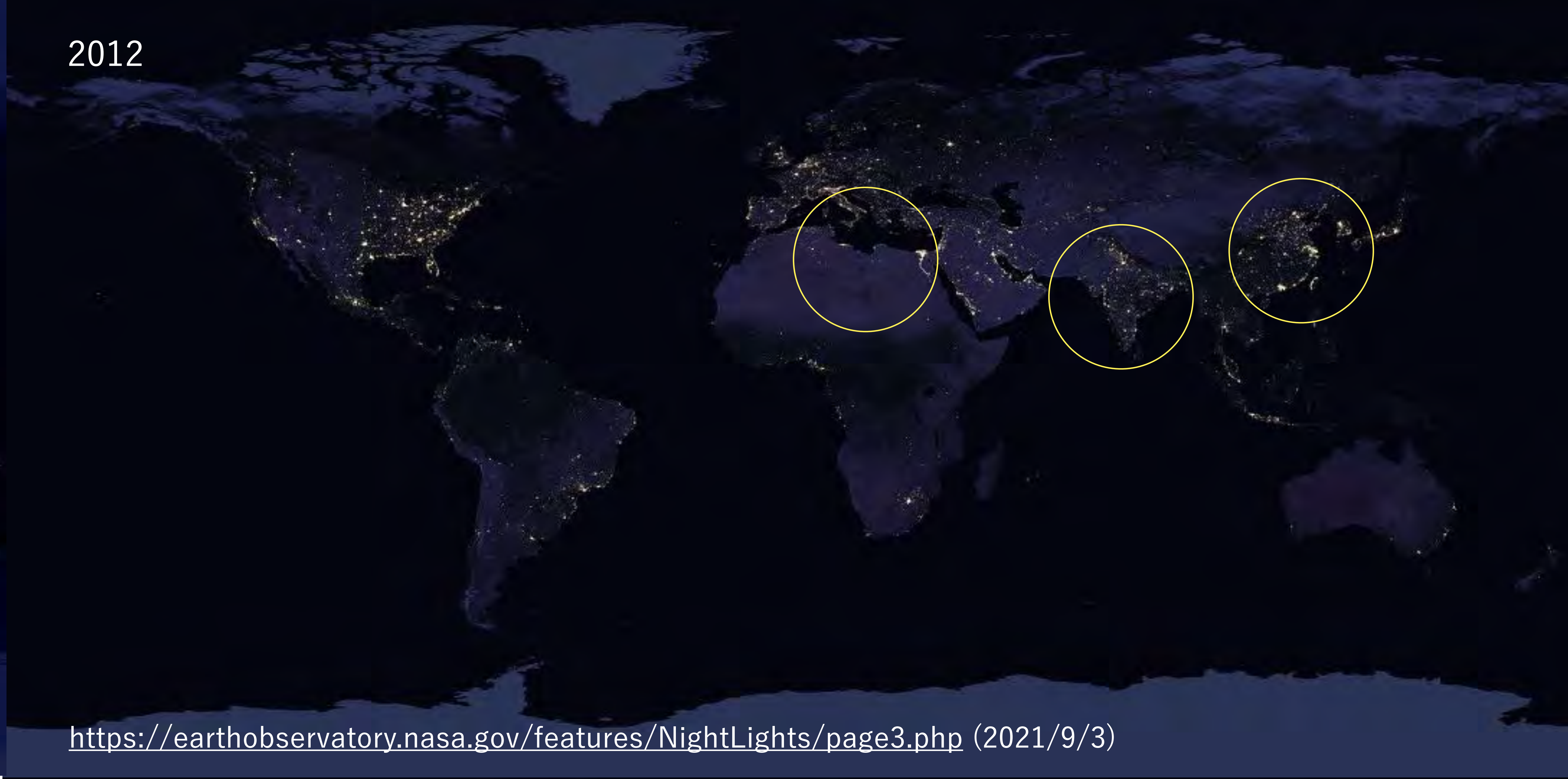
White light source implementation







https://visibleearth.nasa.gov/images/55167/earths-city-lights (2021/9/3)



https://earthobservatory.nasa.gov/features/NightLights/page3.php (2021/9/3)

Energy-efficient LED lights up the world brighter than ever.

https://earthobservatory.nasa.gov/features/NightLights/page3.php (2021/9/3)

Light emitting data (LED)

Visible Light Communication (VLC)

1999　Proposed by Prof. Masao Nakagawa, Keio University

2001　Visible Light Communication Consortium

(Chair：Prof. Shinichiro Haruyama, Keio University)

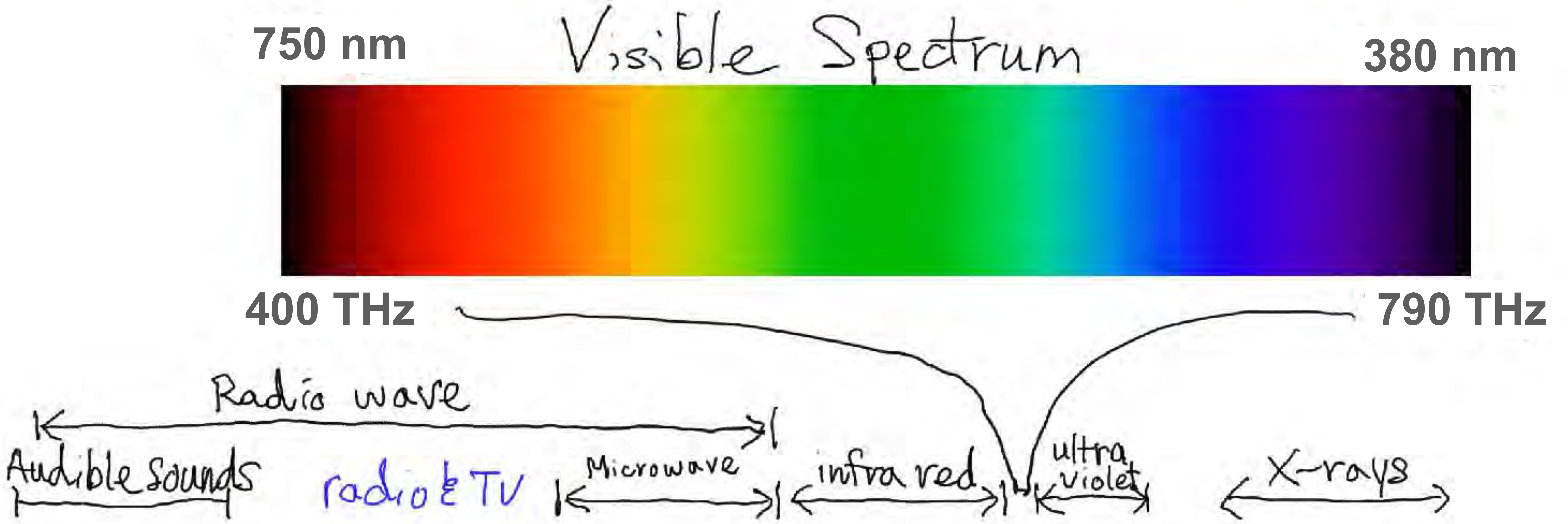
2014　Visible Light Communications Association

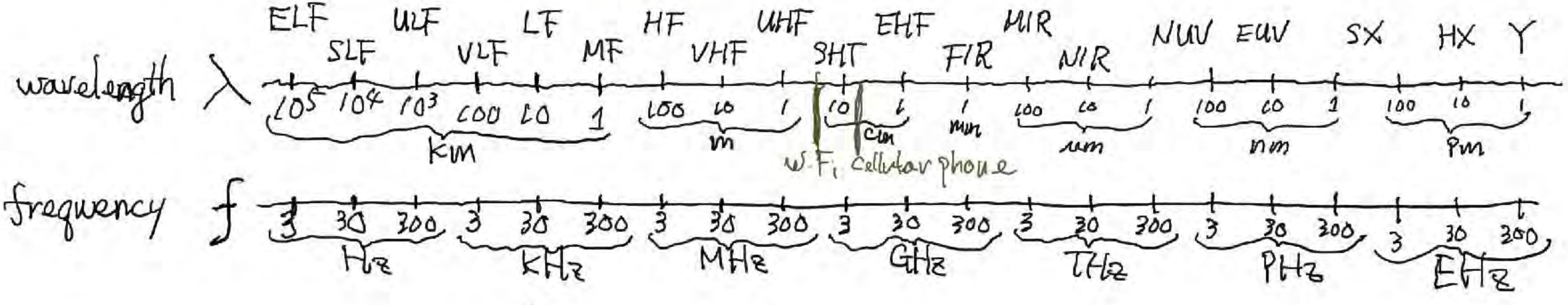
2023　JPC Optical Wireless Group (Chair: Prof. Yamazato)

http://www.vlcc.net/modules/xpage1/?ml_lang=en (2021/9/3)　http://www.sdm.keio.ac.jp/en/faculty/haruyama_s.html (2021/9/3)

Electromagnetic spectrum

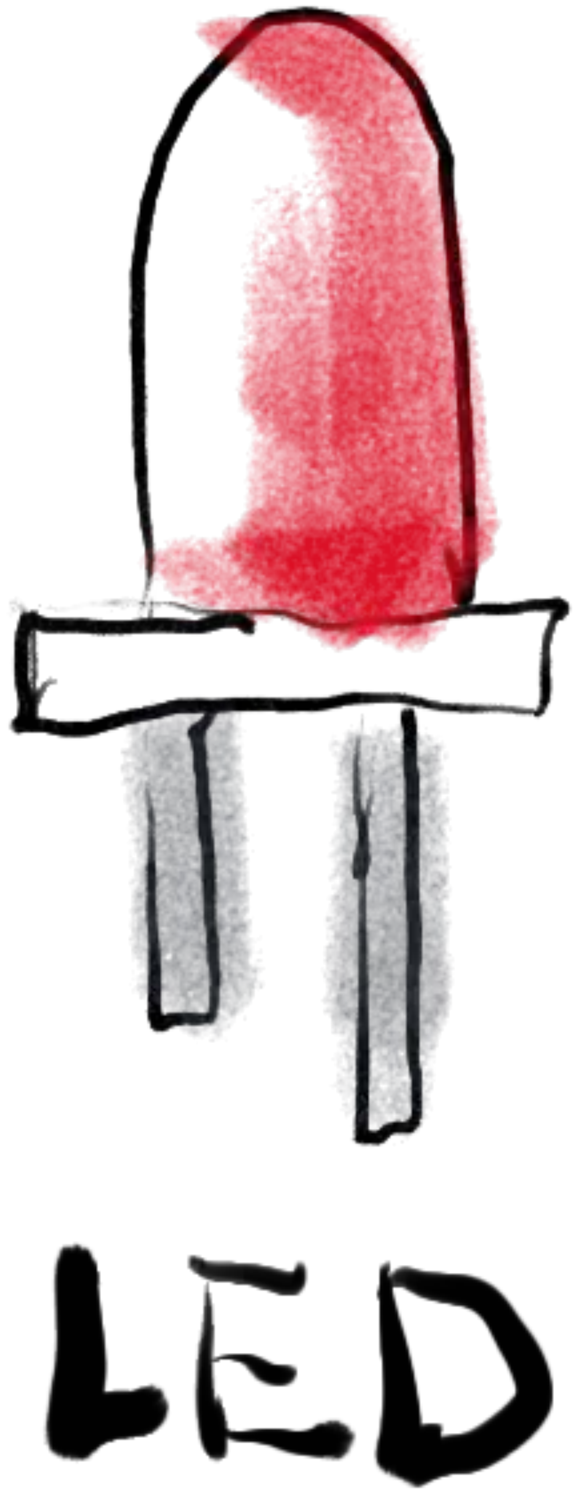
	Class	Wavelength λ	Frequency f
γ	Gamma rays	1 pm	300 EHz
HX	Hard X-rays	10 pm	30 EHz
SX	Soft X-rays	100 pm	3 EHz
		1 nm	300 PHz
EUV	Extreme ultraviolet	10 nm	30 PHz
NUV	Near ultraviolet, visible	100 nm	3 PHz
		1 μm	300 THz
NIR	Near infrared	10 μm	30 THz
MIR	Mid infrared	100 μm	3 THz
FIR	Far infrared	1 mm	300 GHz
EHF	Extremely high frequency	1 cm	30 GHz
SHF	Super high frequency	1 dm	3 GHz
UHF	Ultra high frequency	1 m	300 MHz
VHF	Very high frequency	10 m	30 MHz
HF	High frequency	100 m	3 MHz
MF	Medium frequency	1 km	300 kHz
LF	Low frequency	10 km	30 kHz
VLF	Very low frequency	100 km	3 kHz
ULF	Ultra low frequency	1000 km	300 Hz
SLF	Super low frequency	10000 km	30 Hz
ELF	Extremely low frequency	100000 km	3 Hz





VLC Transmitter

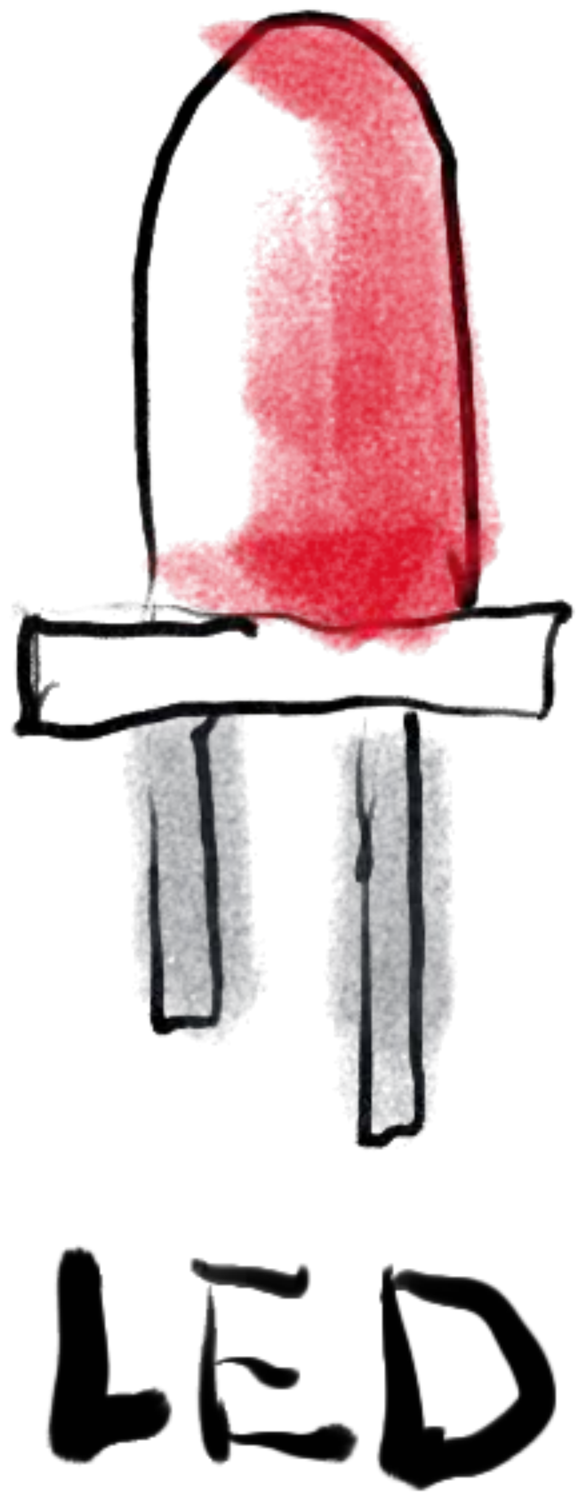
In most cases, VLC uses LEDs for a transmitter.

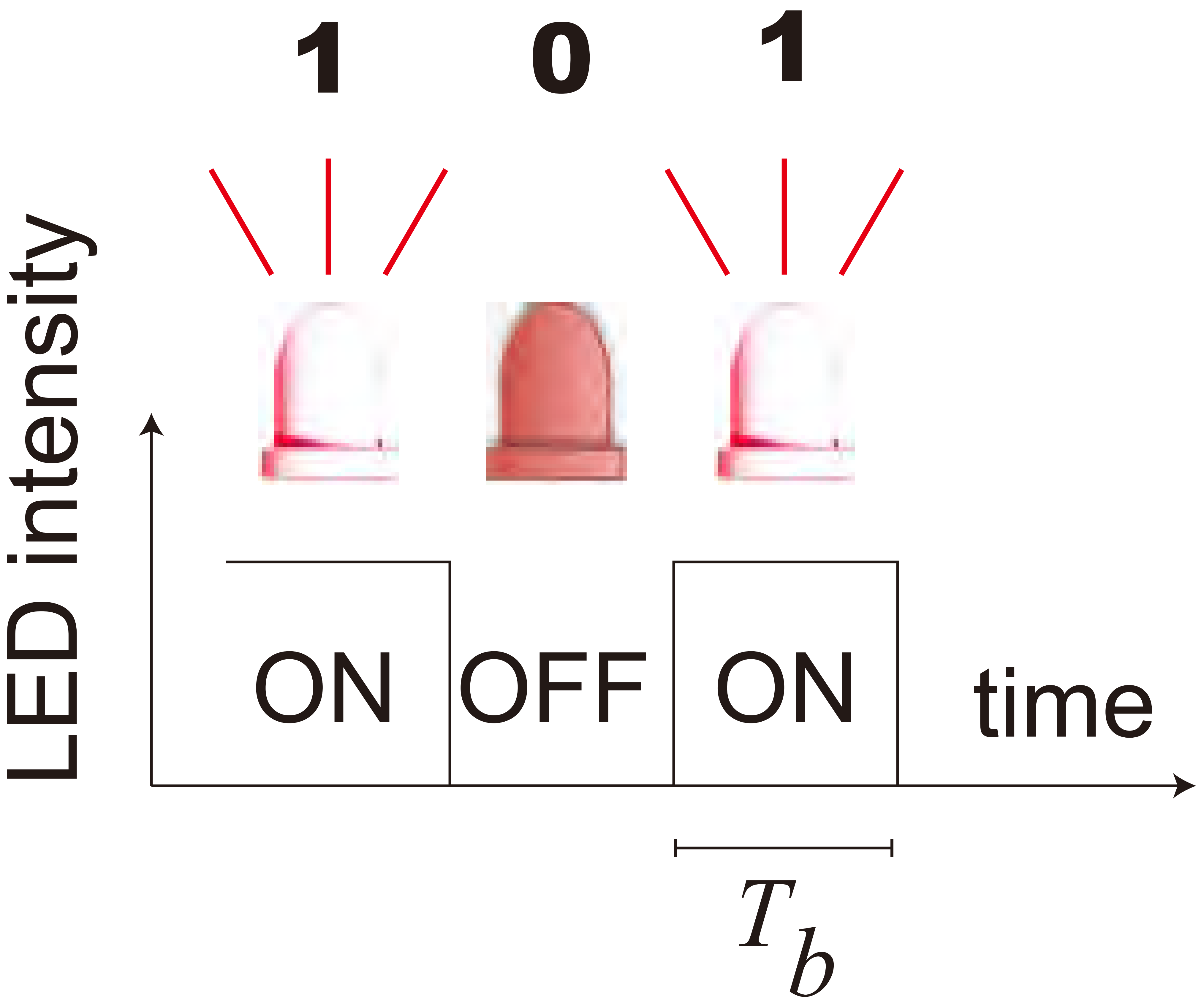


- VLC signal modulation
  - On-off keying (OOK)
  - Pulse-width modulation (PWM)
  - Intensity modulation (IM)
  - Optical orthogonal frequency division multiplexing (optical OFDM)

On-off keying (OOK)

The simplest form of modulation

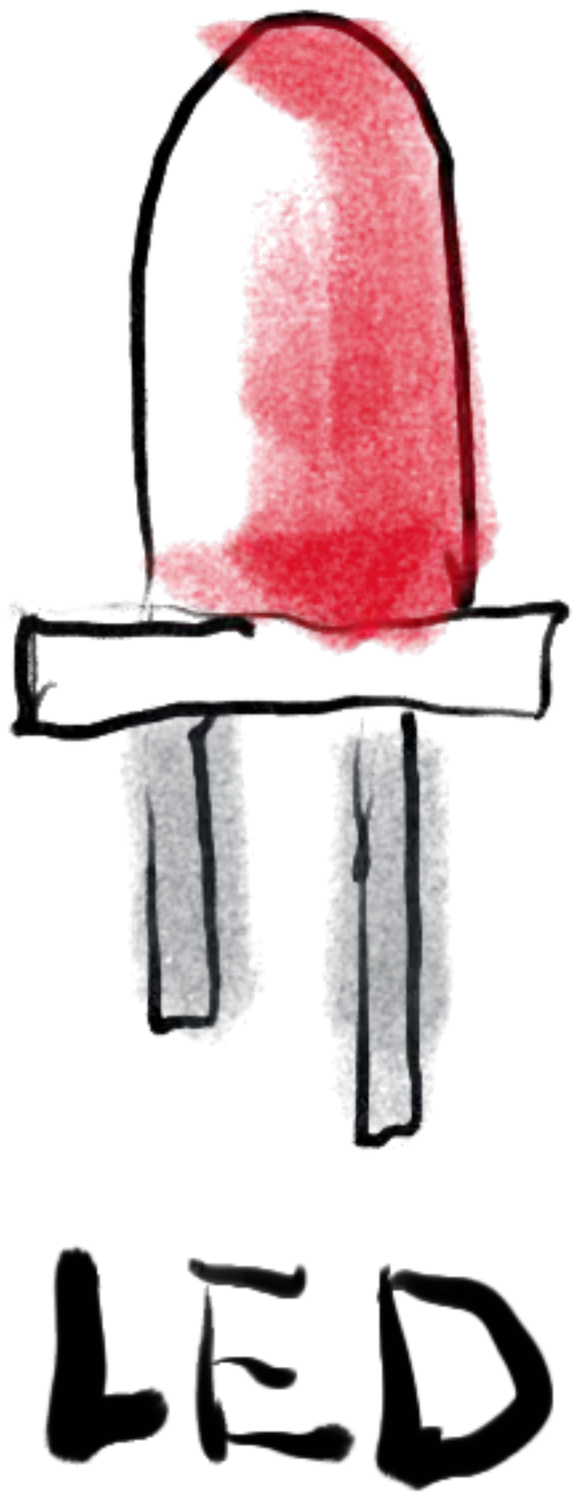


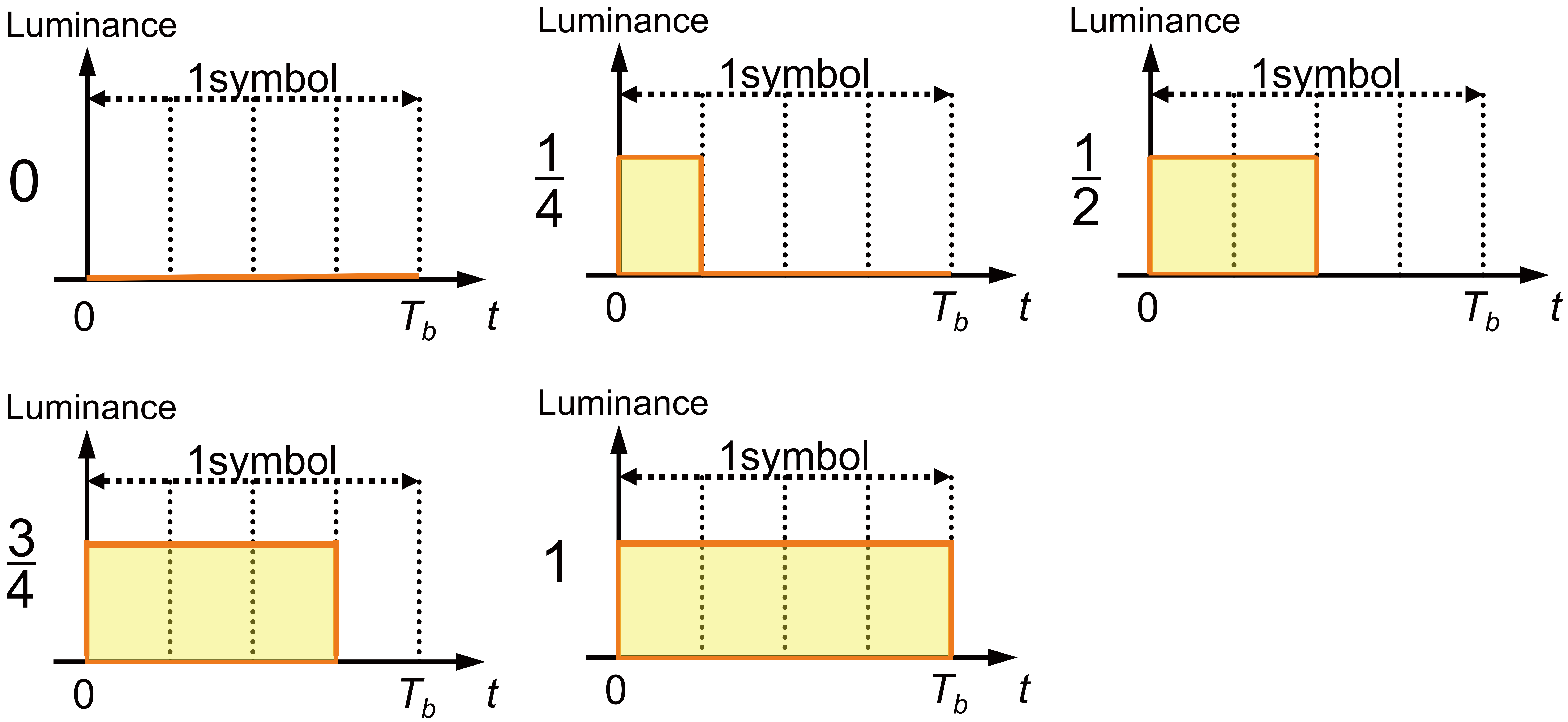


Data rate is $R_b = 1/T_b$

Pulse-width modulation (PWM)

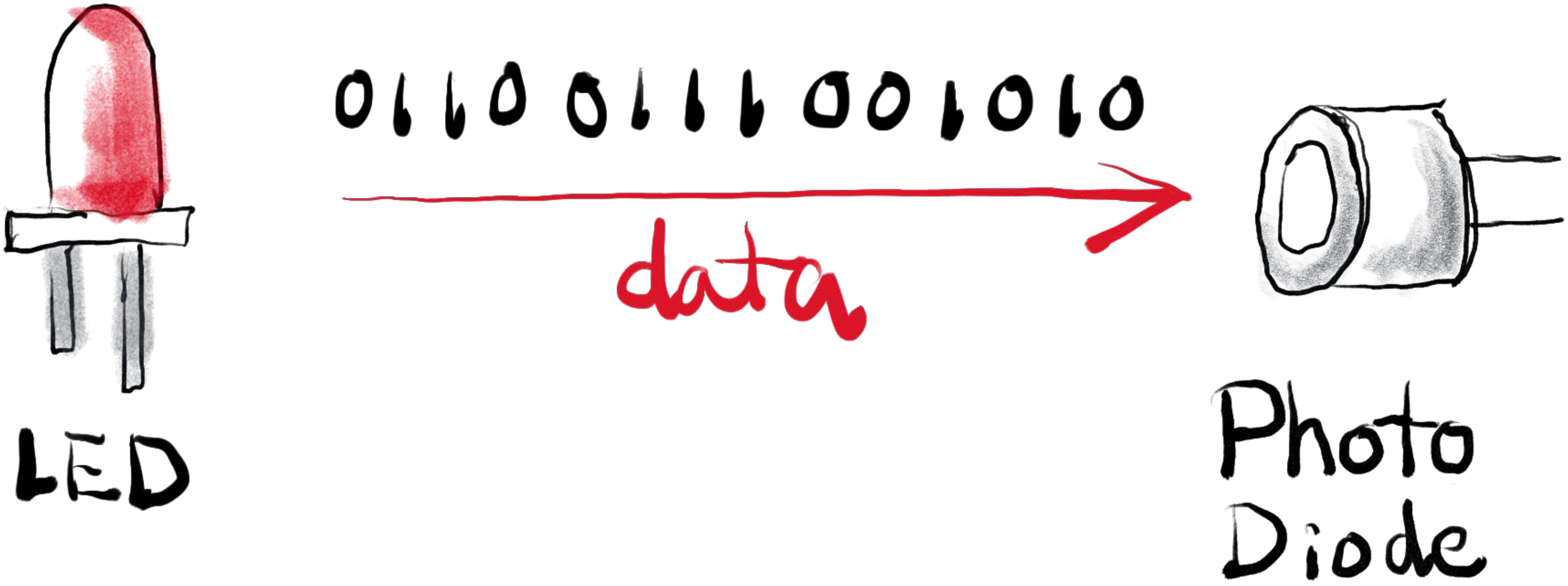
The simplest form of modulation





VLC Transmitter

In most cases, VLC uses LEDs for a transmitter.



Intensity modulation and direct detection (IM/DD) systems

Image sensor communications (ISC)

Image Sensor Communications（ISC）

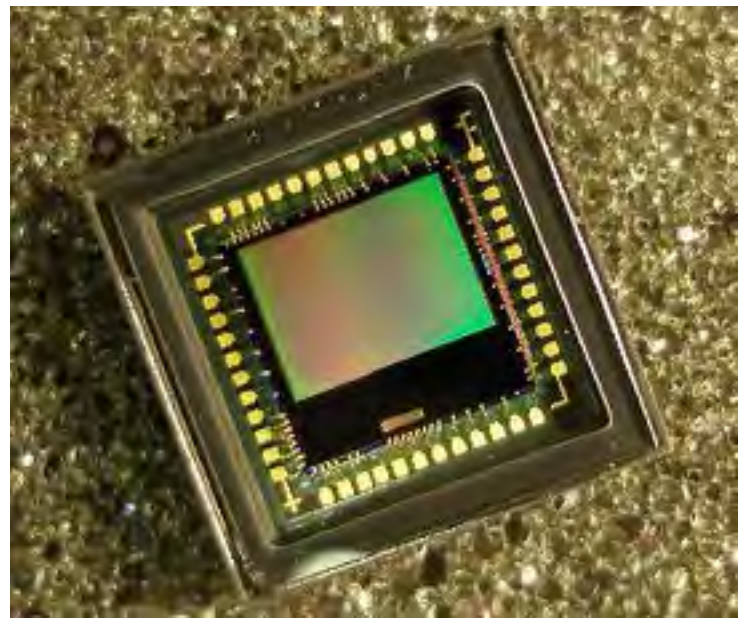
Norio Iizuka, Advisory Engineer, Casio

- Proposed by Mr. Iizuka of Casio Co.
- Basically the same as optical camera communication (OCC) standardized in IEEE 802.15.7
- It has spatial separation characteristics:
  - Spatial separation characteristics enable spatial parallel transmission using LED arrays.
  - Easy tracking of the transmission source
  - Simultaneous communication and ranging (position estimation)

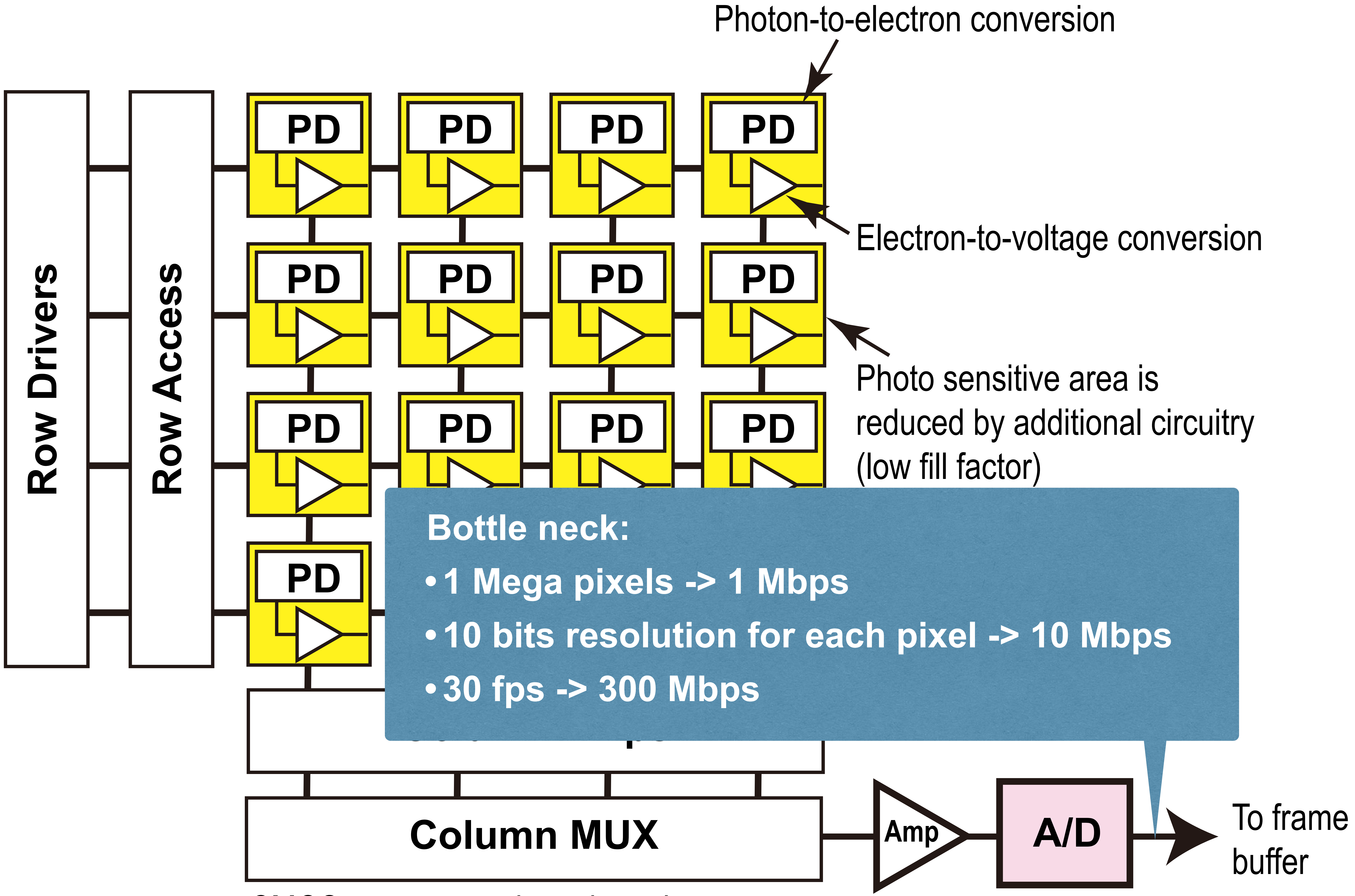
カシオ計算機「ピカリコ」 LED×カメラの可視光通信、“第3の測位技術”注目

https://news.aperza.jp/カシオ計算機「ピカリコ」-ledxカメラの可視光通信/　（閲覧：2022/12/12）

CMOS (complementary metal oxide semiconductor)



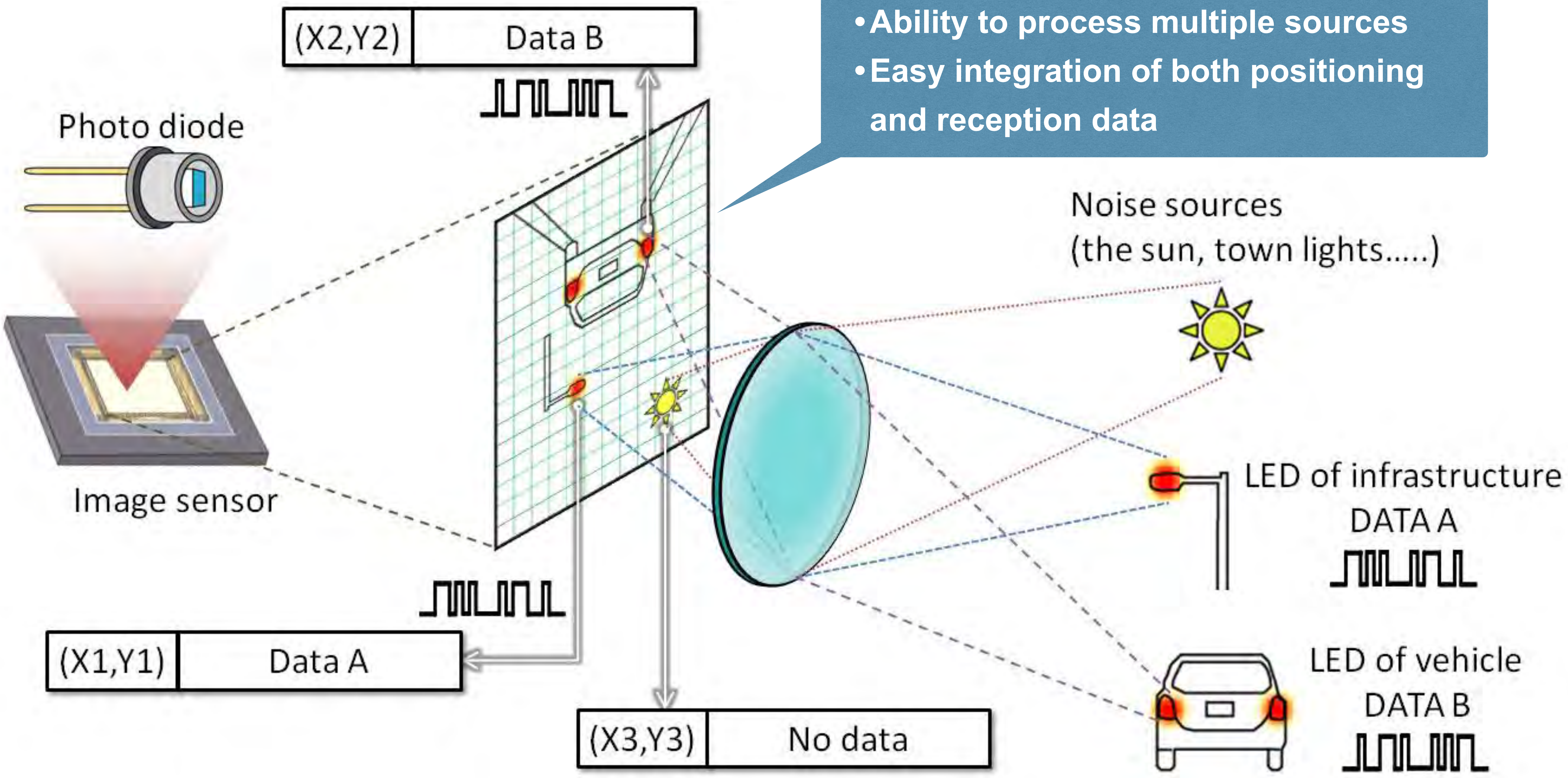
https://en.wikipedia.org/wiki/Active-pixel_sensor



CMOS sensors read out the voltage using row and column decoders, like a digital memory.

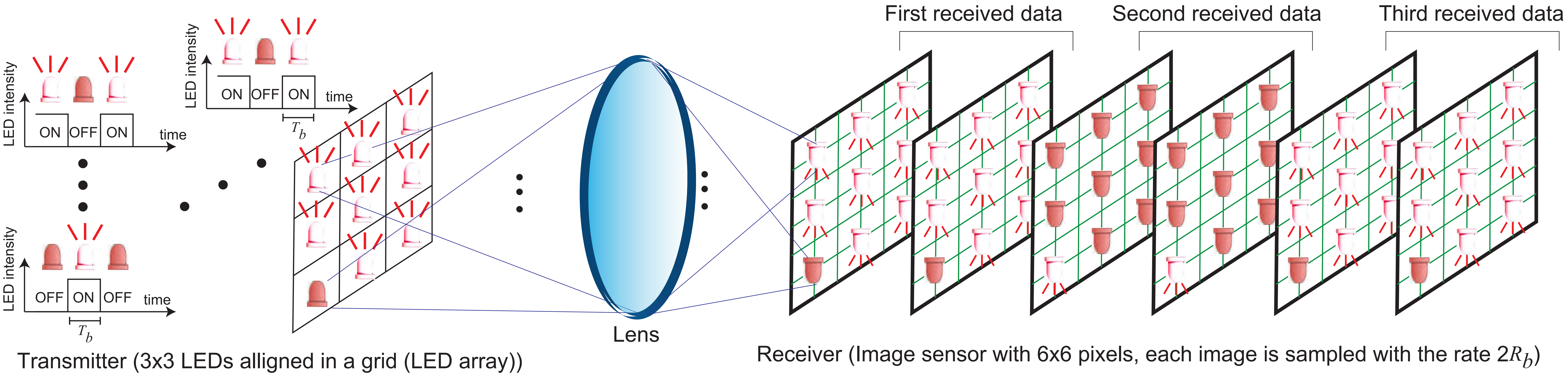
High-Speed Image Sensor as a Reception Device of VLC Signals

Spatial separation of sources
- **Ability to process multiple sources**
- **Easy integration of both positioning and reception data**



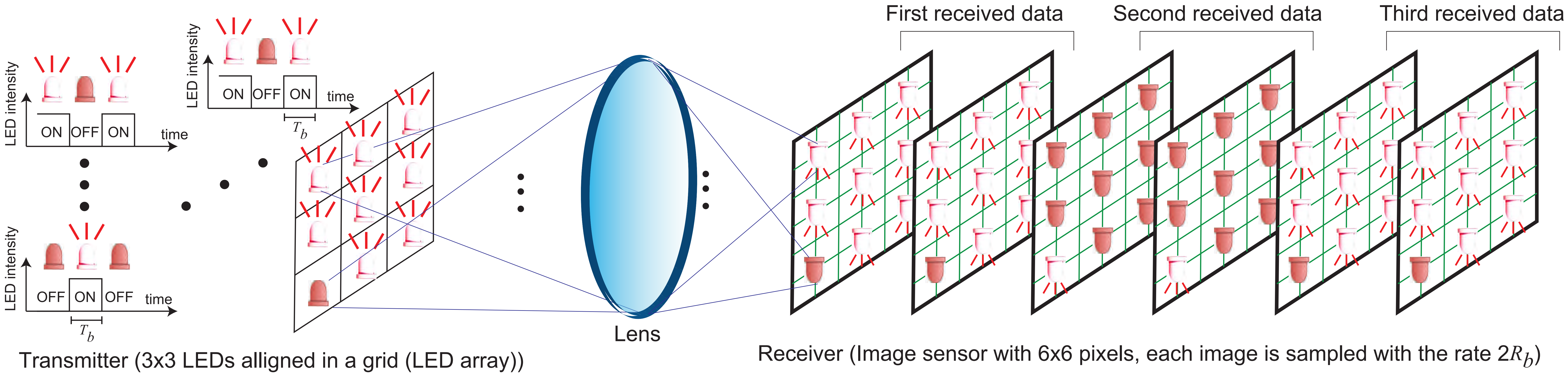
T. Yamazato, et al. "Vehicle Motion and Pixel Illumination Modeling for Image Sensor Based Visible Light Communication," IEEE JSAC, 2015.

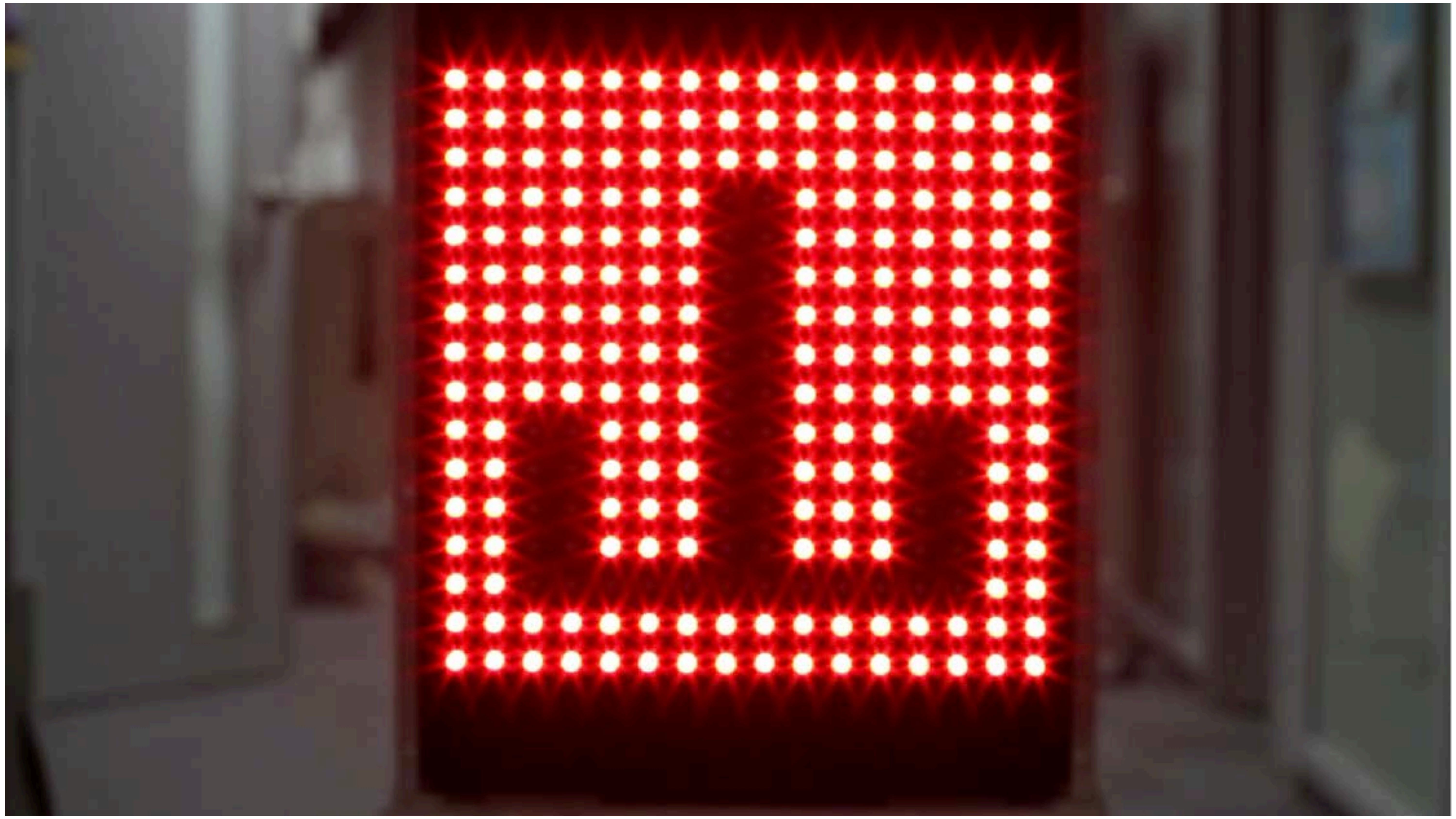
LED array transmitter and Image sensor receiver



- Spatial separation

  Image sensor receiver can receive and process multiple transmitting sources.


LED intensity
ON
OFF
ON
time
T_b
LED intensity
OFF
ON
OFF
time
Lens
First received data
Second received data
Third received data
Transmitter (3x3 LEDs alligned in a grid (LED array))
Receiver (Image sensor with 6x6 pixels, each image is sampled with the rate $2R_b$)



VLC using high-speed camera

How fast can we achieve? — Ideal case —

iPhone
1080p 240 fps

$$1920 \times 1080 \times 240\ fps \times 12\ bit \times 3\ colors$$

Considering Nyquist sampling (1/2)

$$960 \times 540 \times 120\ fps \times 6\ bit \times 3\ colors$$

Spatial

Temporal

Dynamic range

1,119,744,000 bps (**1.1 Gbps**)

Xperia
1080p 920 fps

$$1920 \times 1080 \times 920\ fps \times 12\ bit \times 3\ colors$$

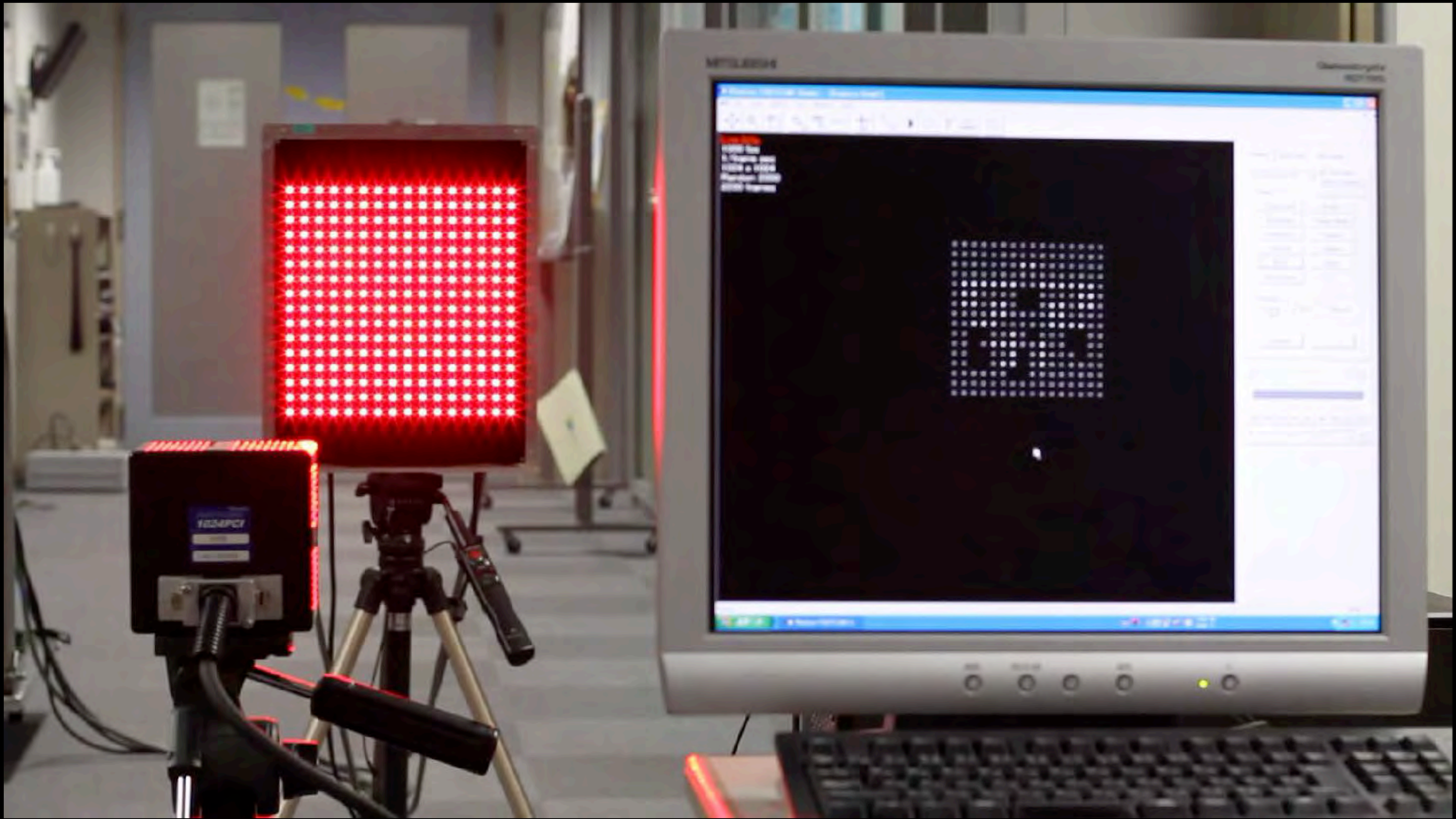
Considering Nyquist sampling (1/2)

$$960 \times 540 \times 460\ fps \times 6\ bit \times 3\ colors$$

4,292,352,000 bps (**4.3 Gbps**)

LED array: 500 Hz

High-speed camera: 1000 fps



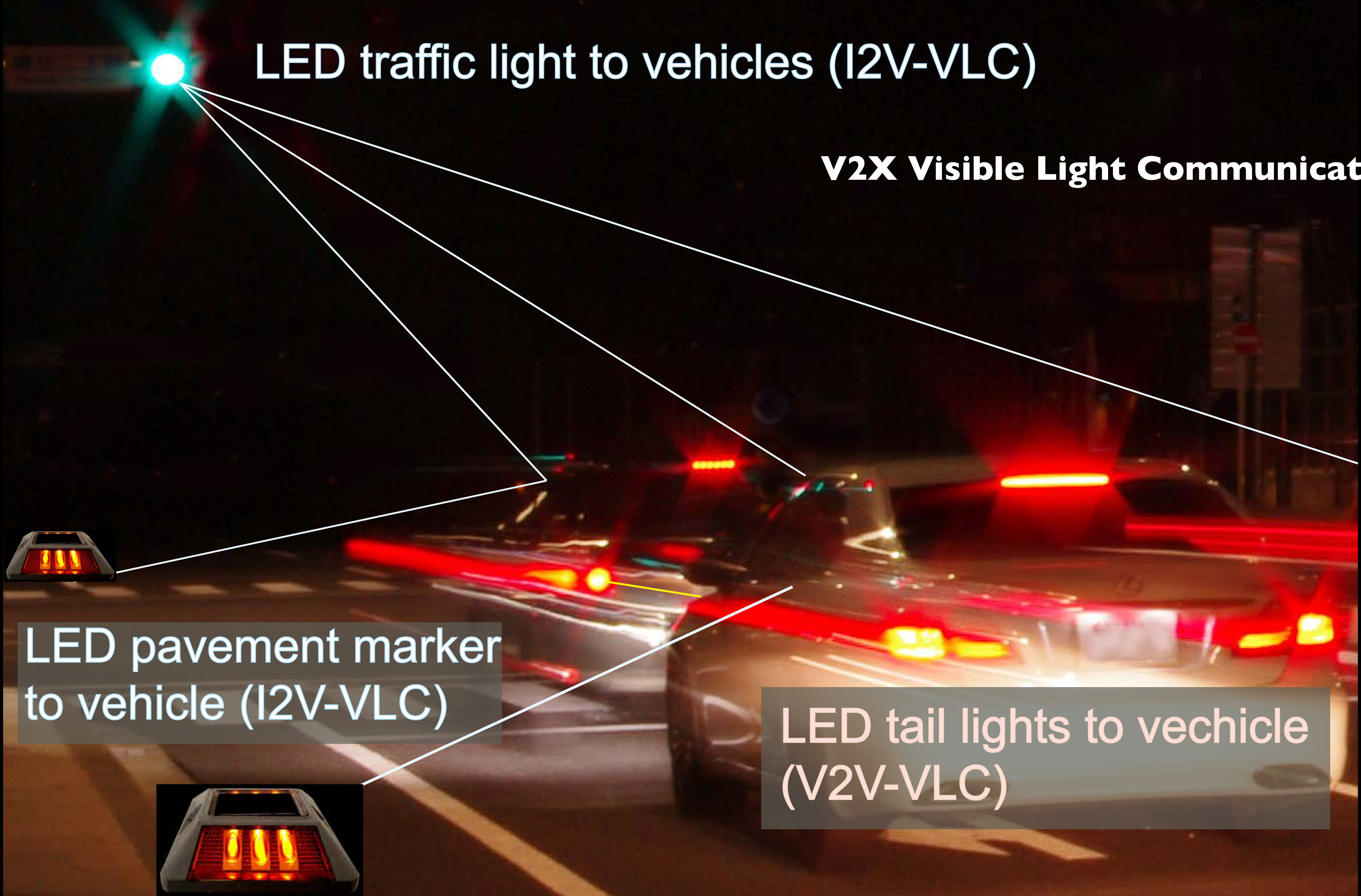
High-speed Image Sensor

160 km/h

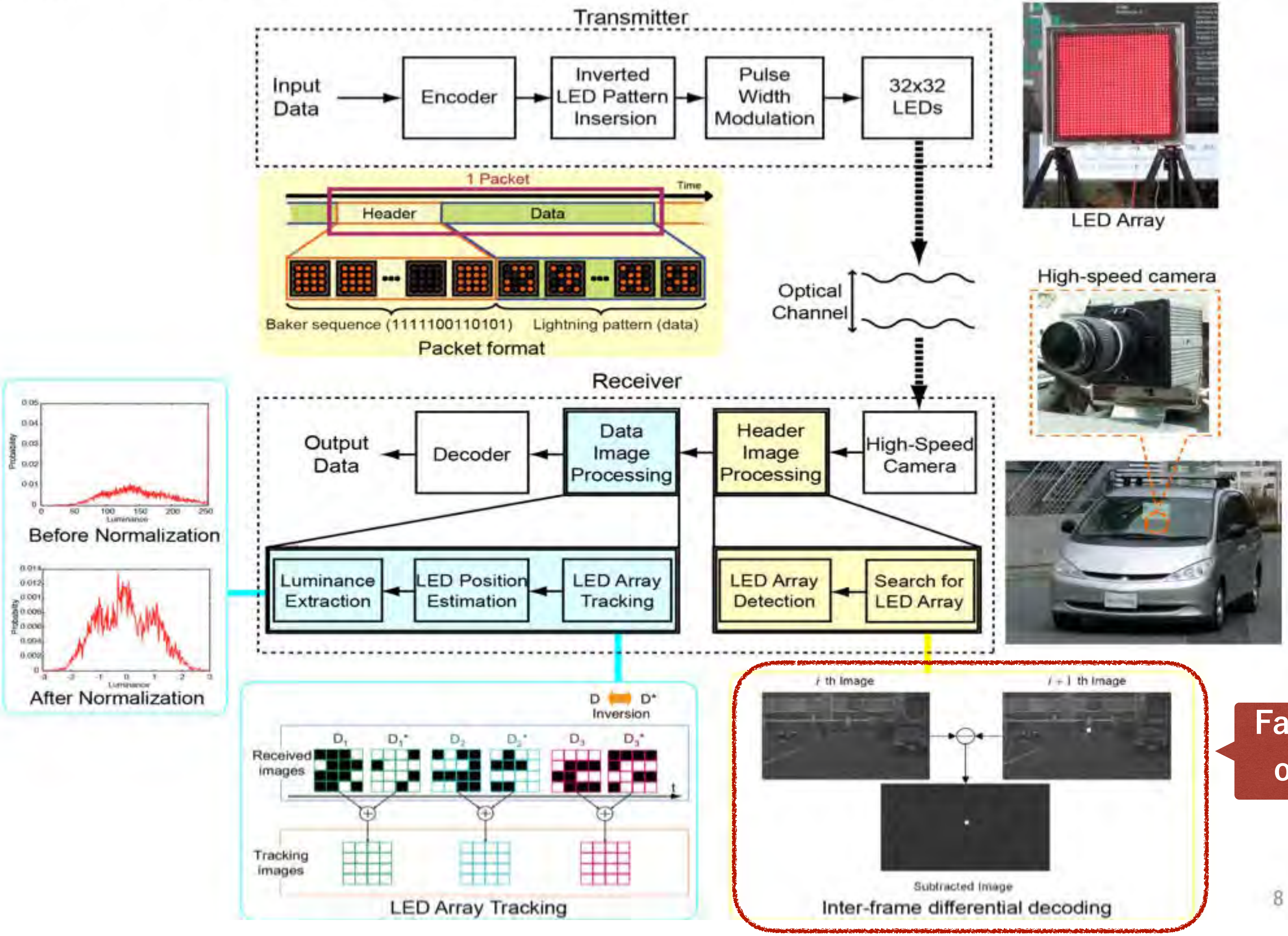
I. Ishii, et al, “High-frame-rate optical flow system,” IEEE Trans. on Circuits and Systems for Video Technology, Jan. 2012.

Prof. Ishii, Hiroshima University

High-speed image processing for automotive applications


LED traffic light to vehicles (I2V-VLC)
V2X Visible Light Communication
LED pavement marker to vehicle (I2V-VLC)
LED tail lights to vechicle (V2V-VLC)

Vehicle-to-Infrastructure Visible Light Communications (V2I-VLC) System



Fast recognition of LED arrays

T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.

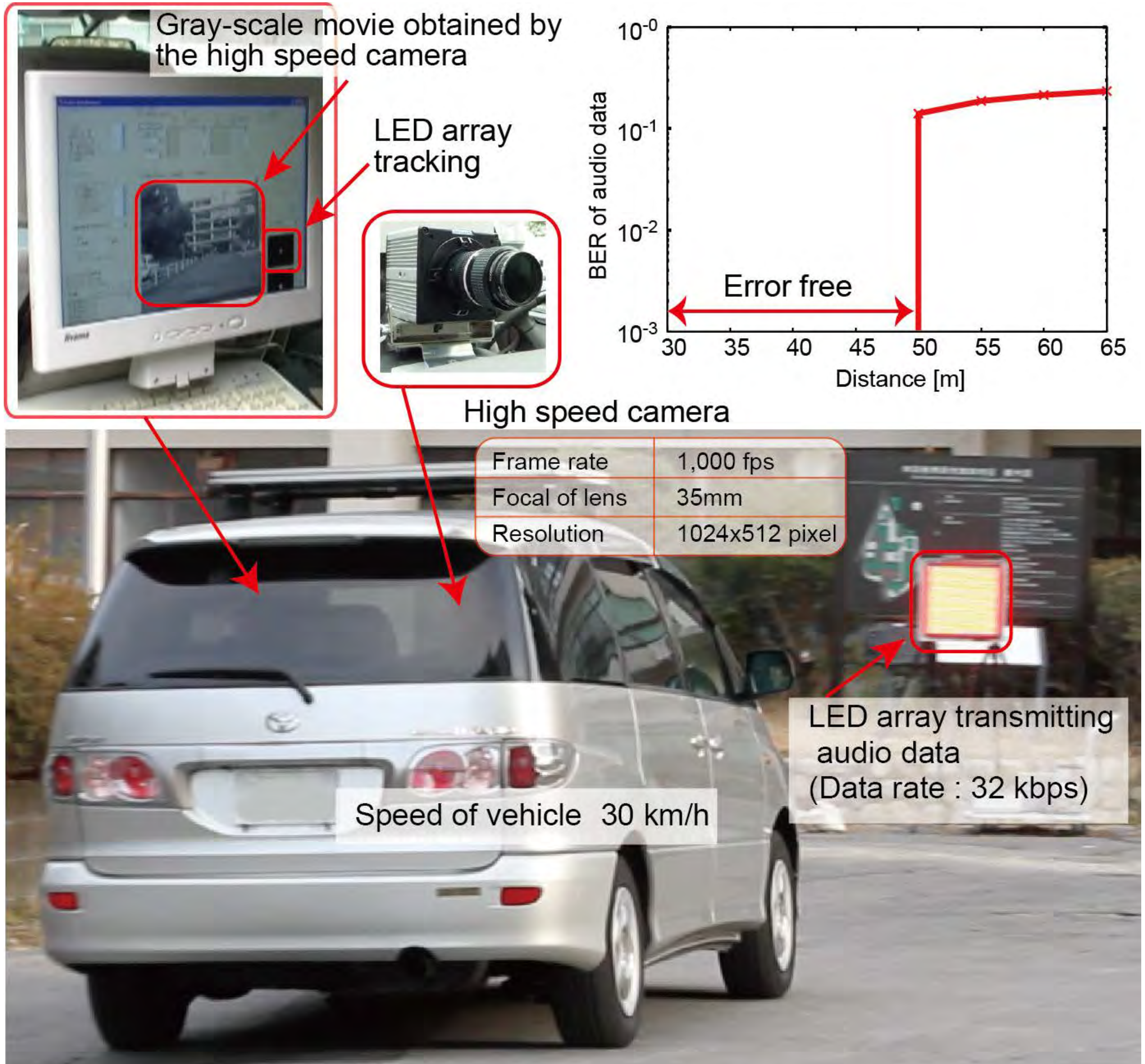
Fast recognition of LED arrays

Two consecutive images → two consecutive image differences → Binarization →

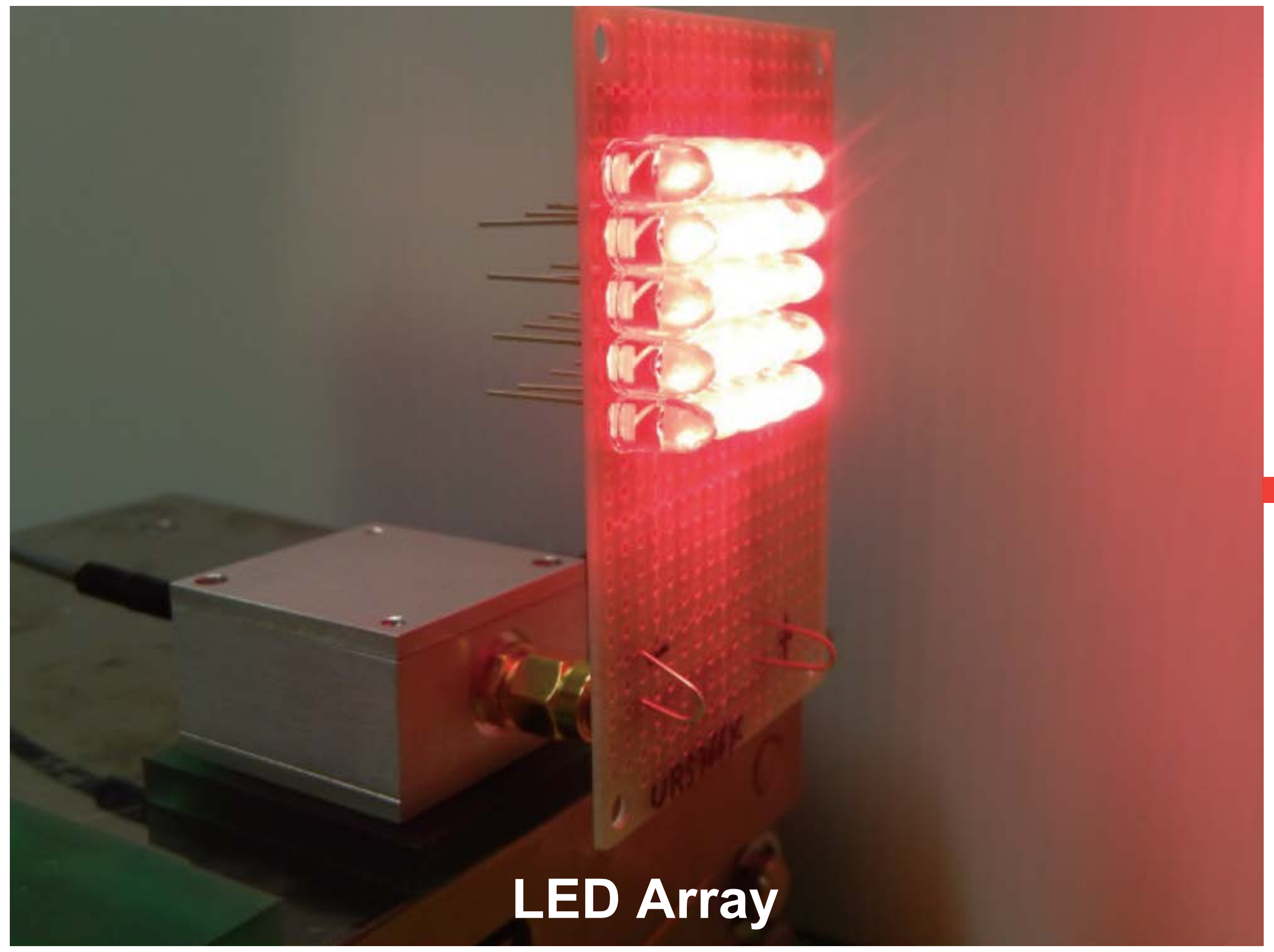
Nth image

2ms

N+1th image

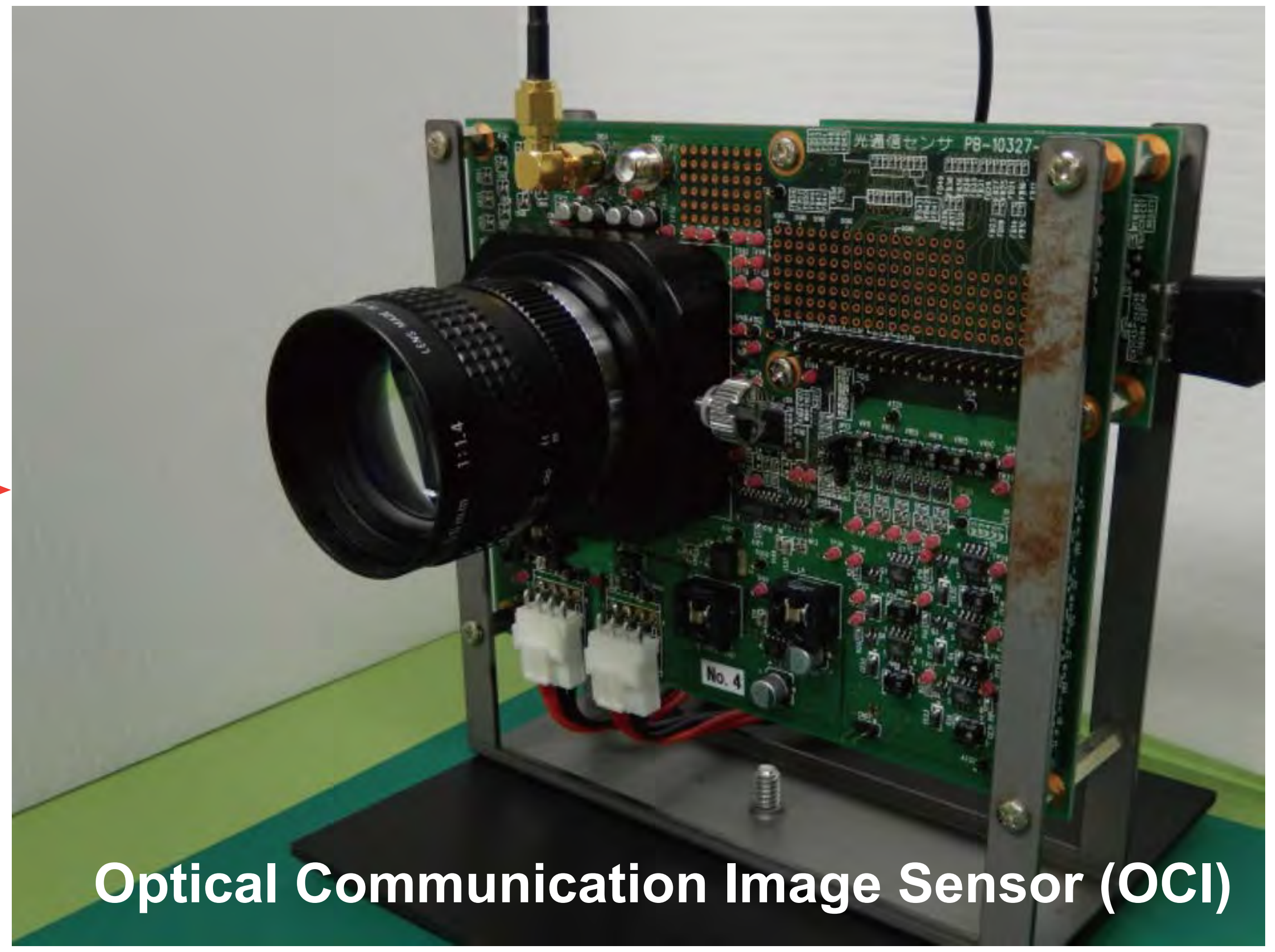


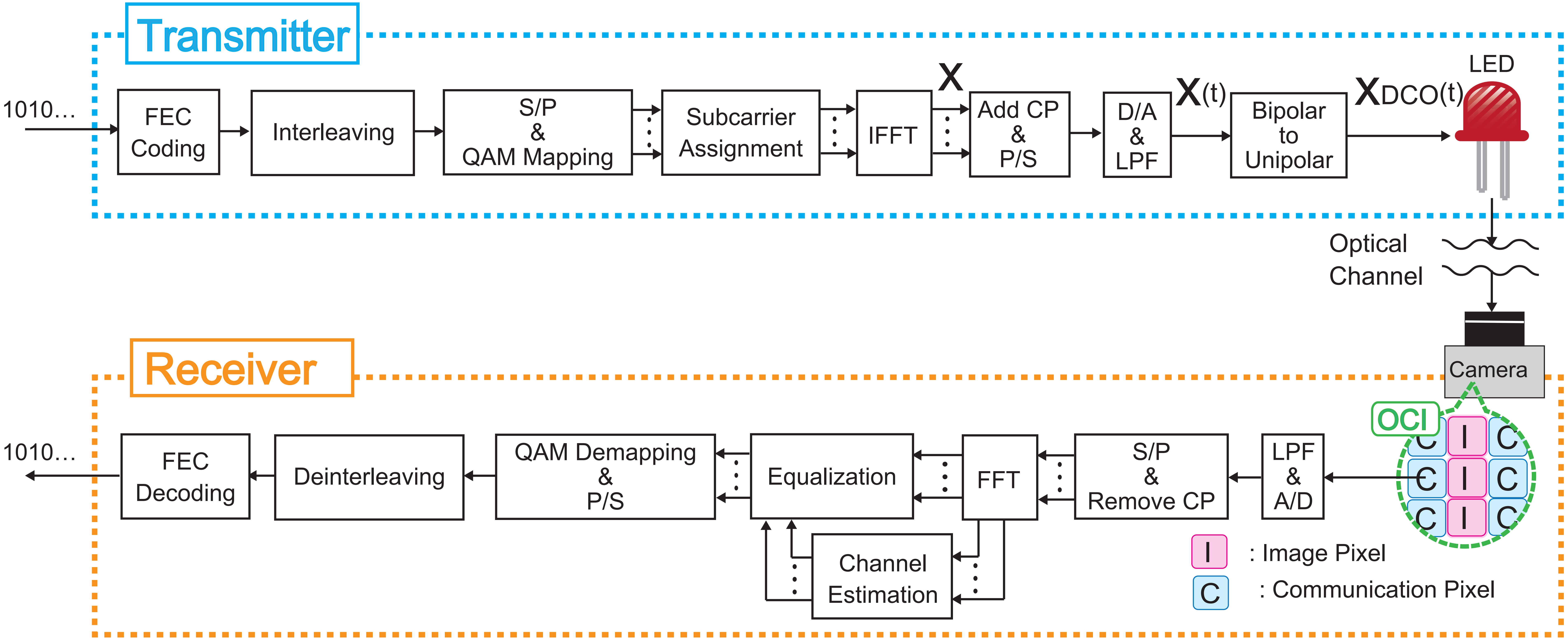
T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.



OCI-based Optical-OFDM

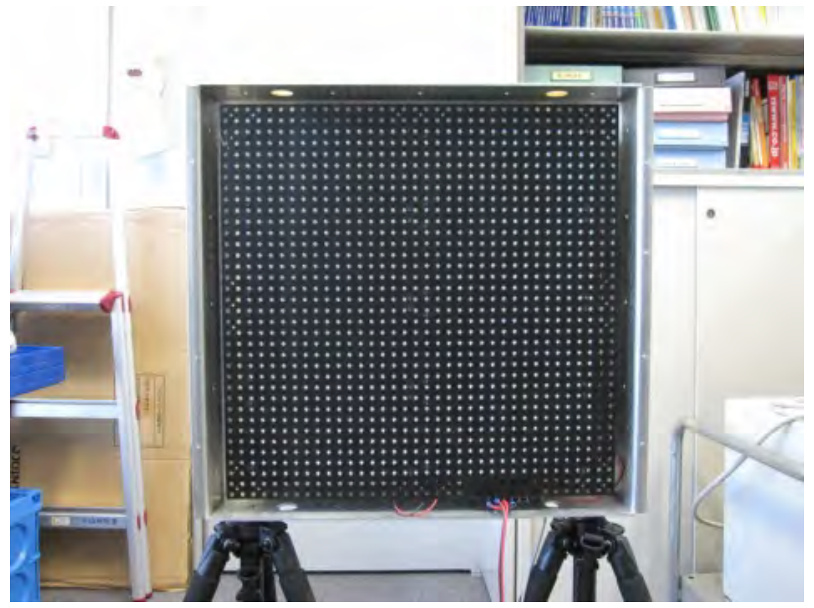
- New automotive VLC system
- 55 Mbps VLC signal transmission
- Faster than DSRC

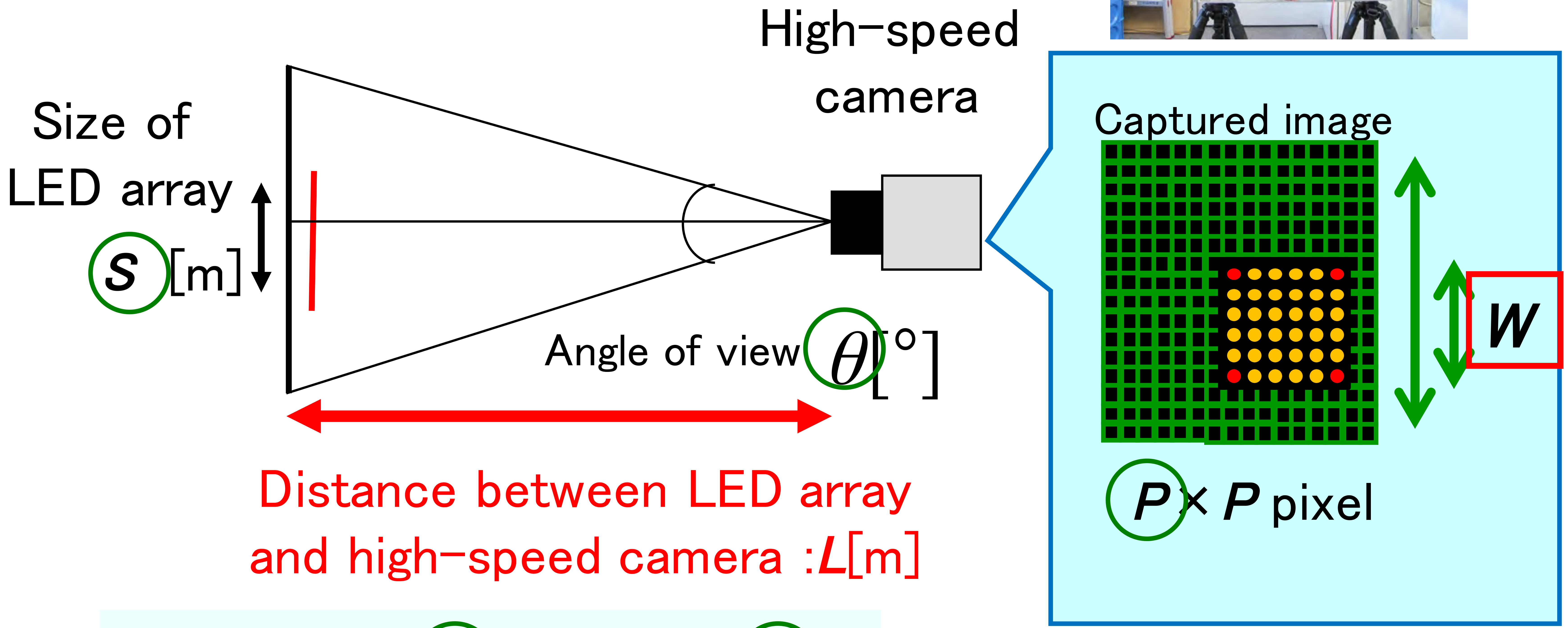




Y. Goto et al. "A New Automotive VLC System Using Optical Communication Image Sensor," IEEE Photonics Journal, Vol. 8, No. 3, June 2016.

How we estimate distance using only one camera

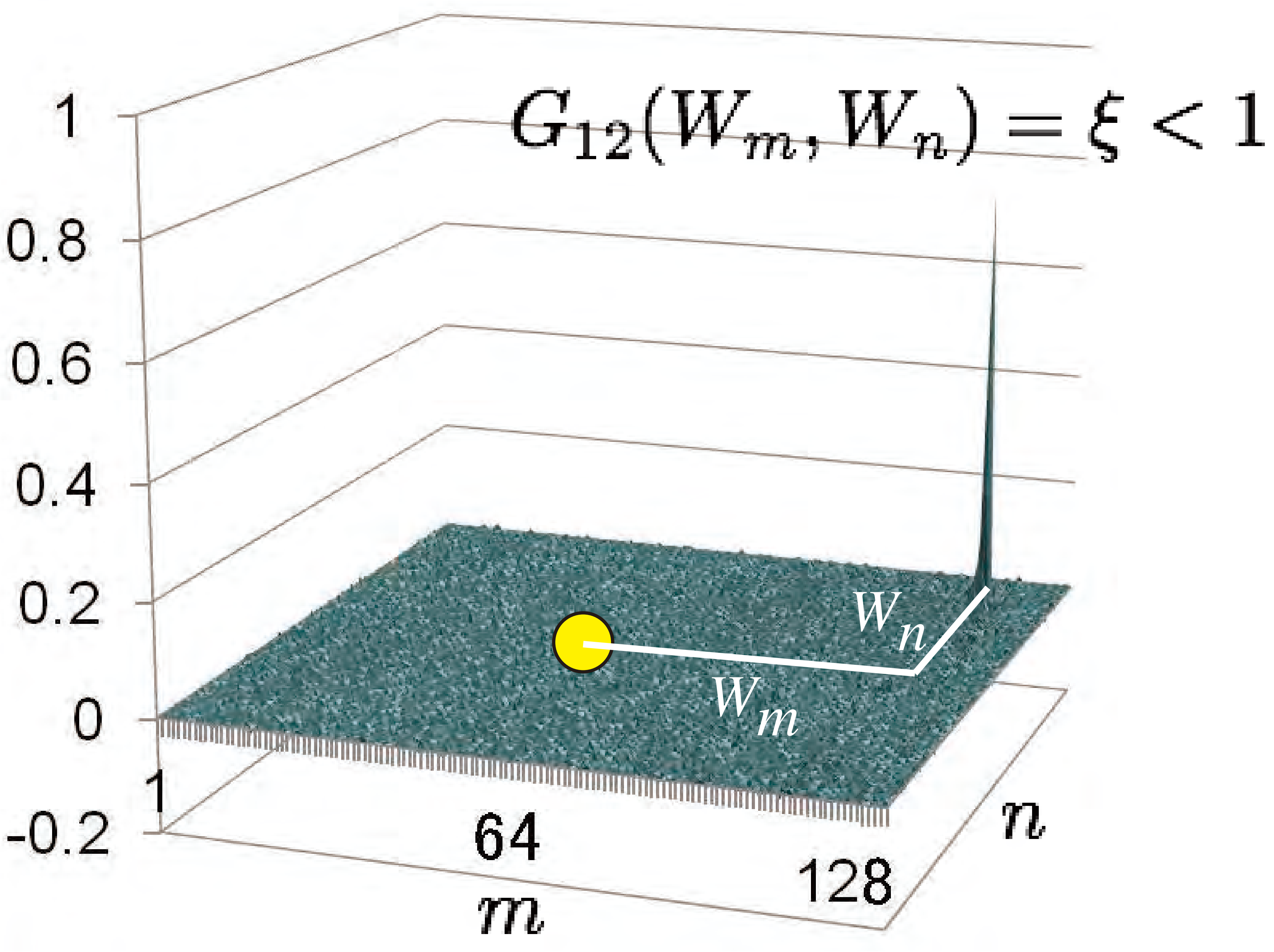




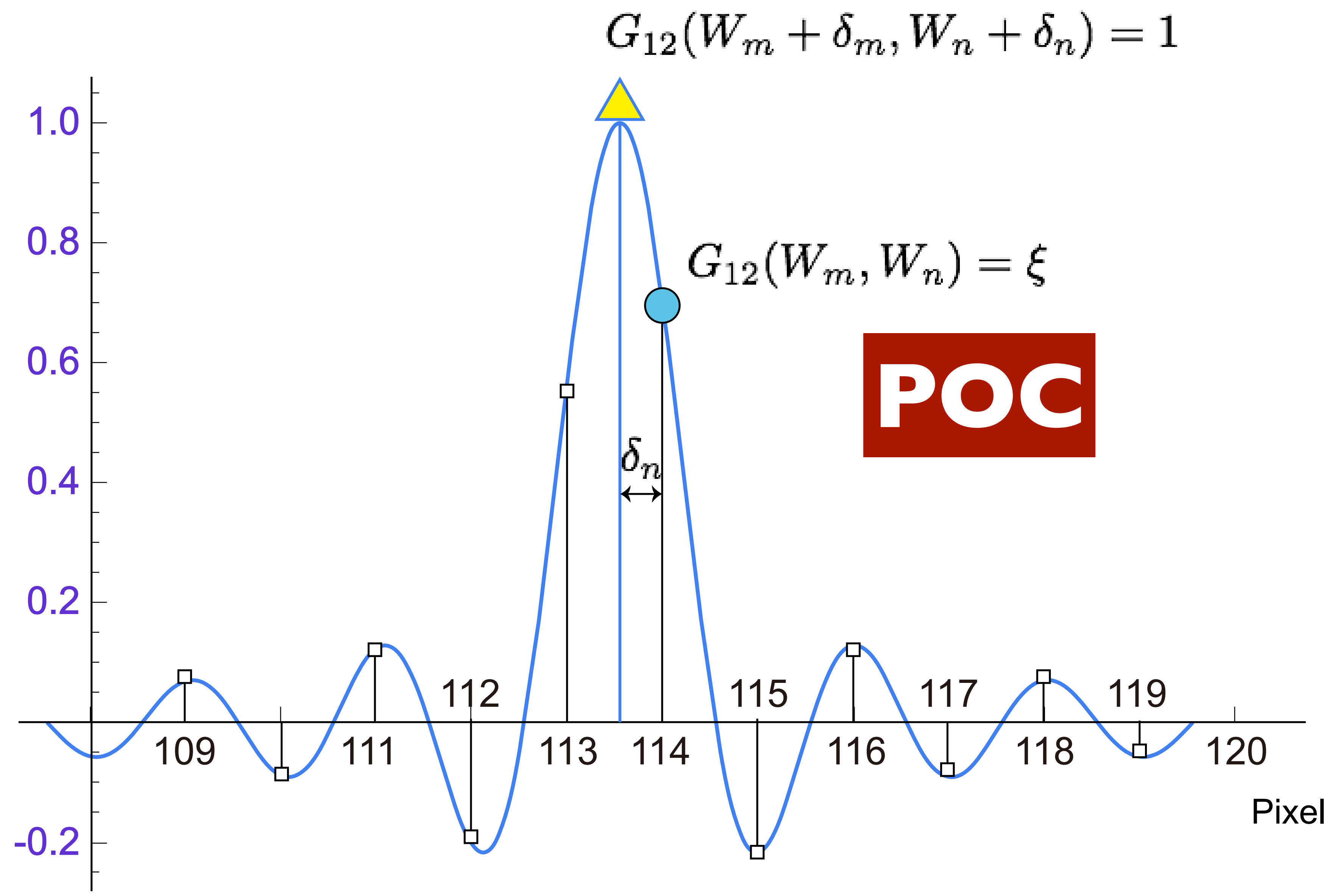
$$\boxed{L} = \frac{1}{2} S \frac{P}{\boxed{W}} \tan^{-1}\left(\frac{\theta}{2}\right)$$

We can estimate distance by using parameter *W*

Phase-only correlation (POC) result and Sinc function approximation

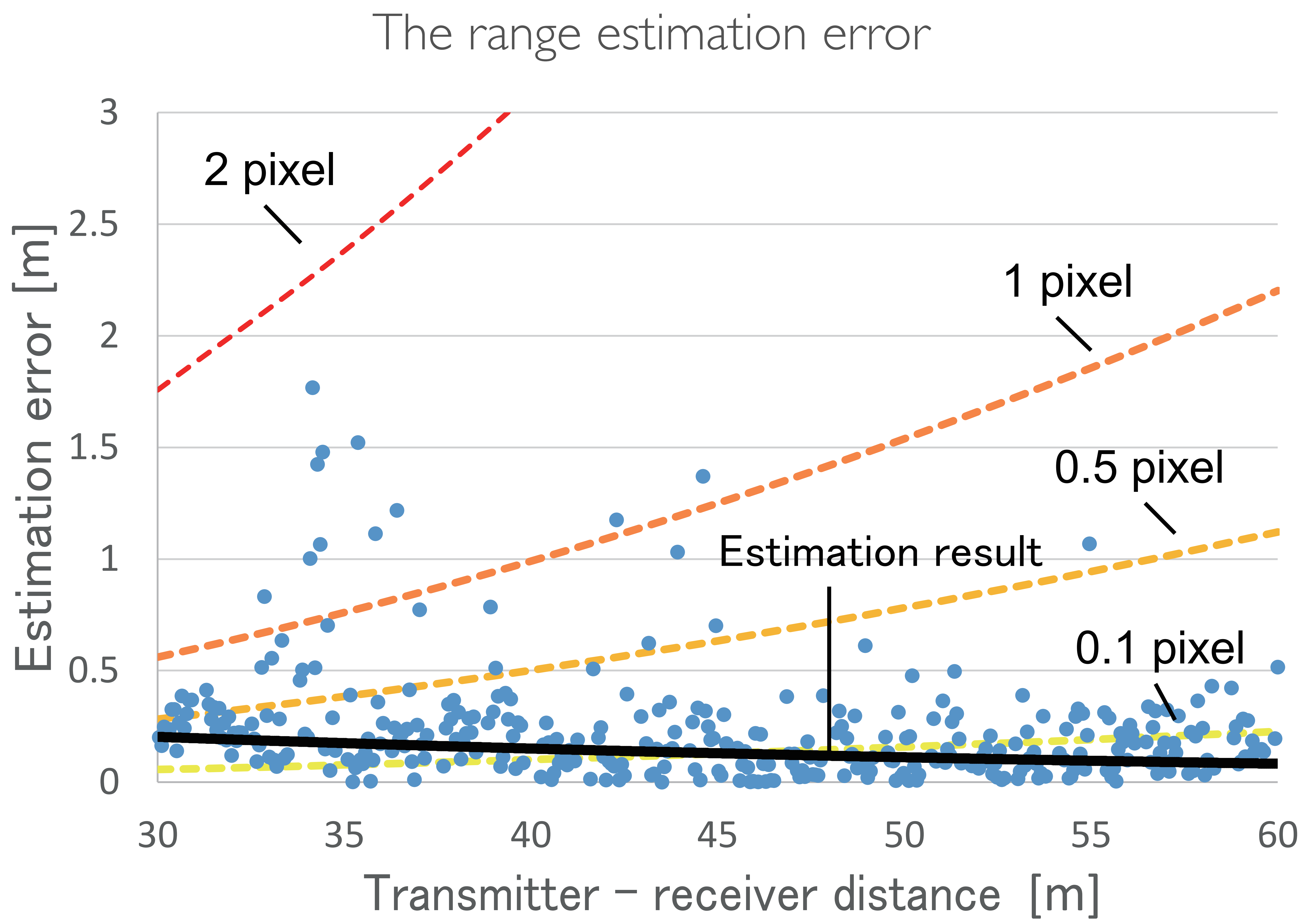


Sinc-approximation



$$G_{k,k+1}(m,n) \simeq \mathrm{sinc}(m + \Delta_m)\,\mathrm{sinc}(n + \Delta_n) \qquad (2)$$

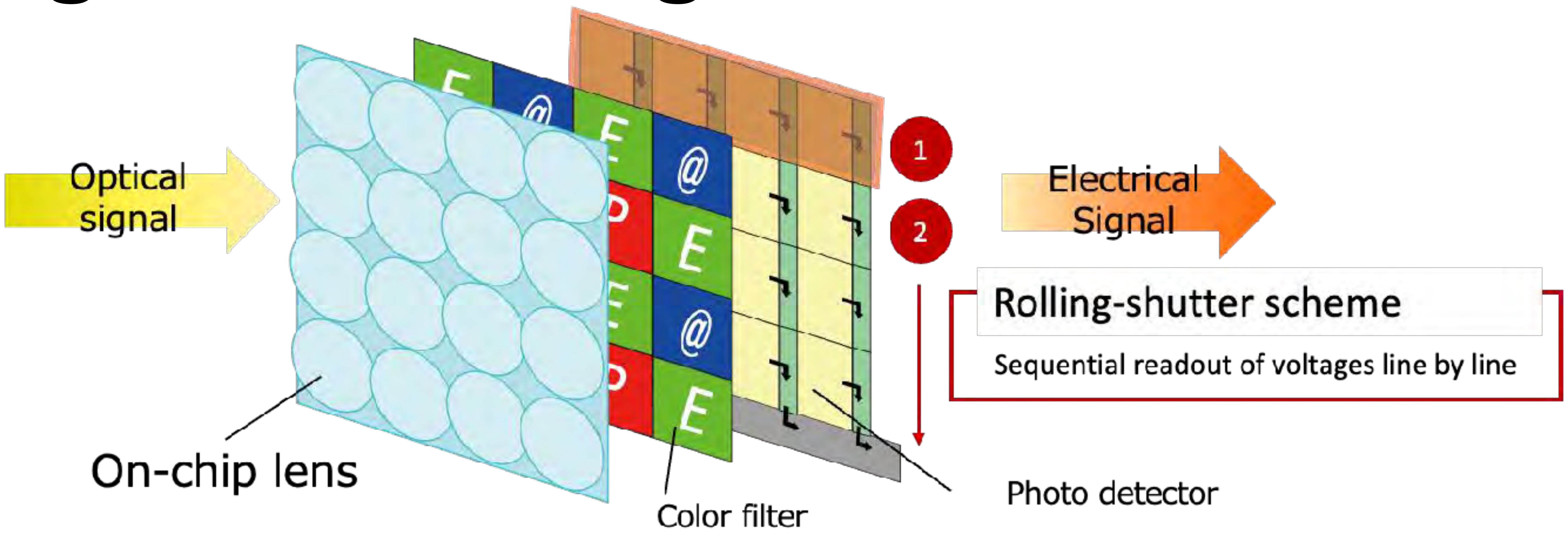
Estimate the displacement in sub-pixel order

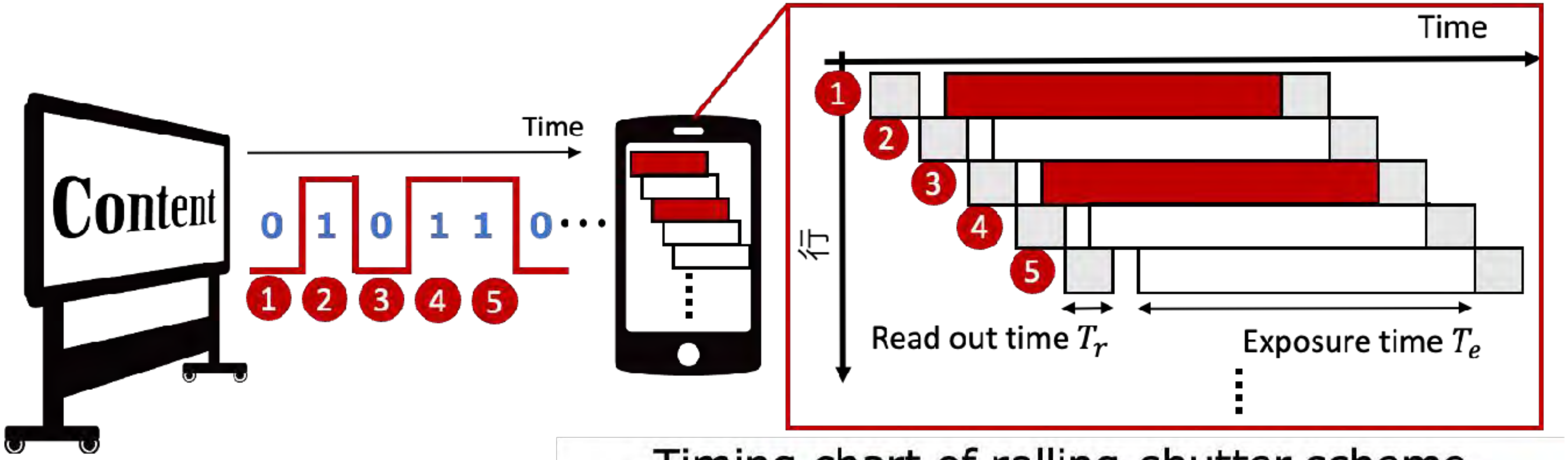


The range estimation error plots along with numerically obtained error curves assuming sub-pixel error.
The curves labeled 2-pixel and 1-pixel are the case without POC while the curves labeled 0.5-pixel and 0.1-pixels are the case with POC.
The black solid curve is the approximate curve of the range estimation (plots).

ISC using Rolling-shutter image sensor

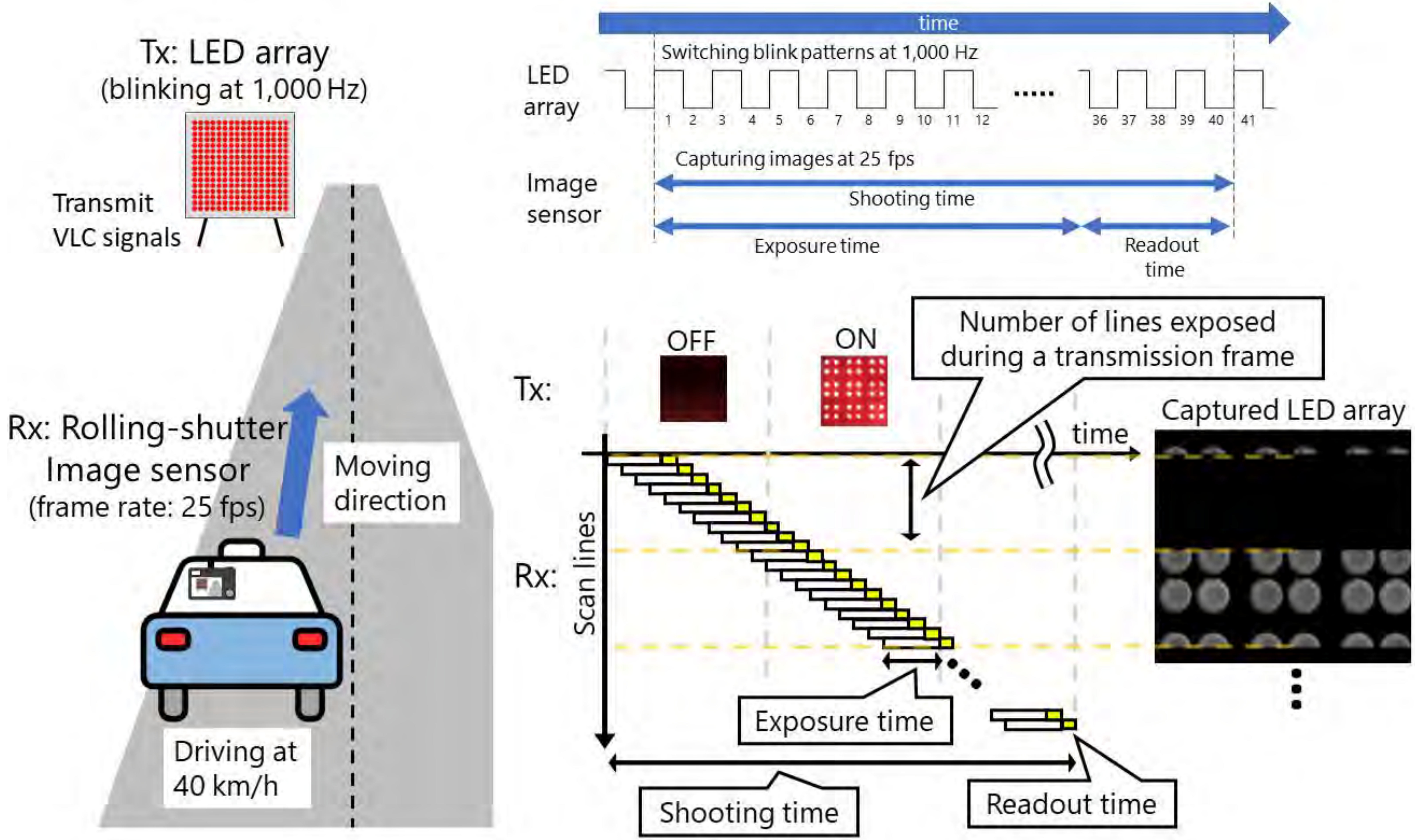
Rolling-shutter image sensor





Timing chart of rolling-shutter scheme

Achieving Successful VLC Signal Reception Using a Rolling Shutter Image Sensor While Driving at 40 km/h



S. Kamiya *et al.*, "Achieving Successful VLC Signal Reception Using A Rolling Shutter Image Sensor While Driving at 40 km/h," in *IEEE Photonics Journal*, vol. 15, no. 4, pp. 1-11, Aug. 2023, doi: 10.1109/JPHOT.2023.3287211.

Conclusion

- Brief history of LED and invention of blue LED
- Visible light communications (VLC)
  - Image sensor communications (ISC)
- VLC using high-speed camera
  - High-speed image processing (eyes of robot)
- High-speed image processing for automotive applications
  - Vehicle to infrastructure visible light communication system
    - Successful audio signal transmission at driving speed of 30 km/h
    - 55Mbps VLC signal transmission (faster than DSRC)
  - Range estimation using POC
    - Estimation error of less than 0.5 m from a 30-60 m range
  - ISC using Rolling-shutter image sensor
    - Successful VLC signal reception using a rolling shutter image sensor while driving at 40 km/h

Thank you and your questions or comments are welcome!
https://yamazato.nuee.nagoya-u.ac.jp/