Visible Light Communication for Automotive

Takaya Yamazato, Nagoya University
yamazato@nagoya-u.jp

Visible Light Communication for Automotive

1. Blue LED
2. Visible light communication (VLC)
3. VLC using high-speed camera
4. High-speed image processing for automotive applications

Blue LED

Google Map: https://www.google.co.jp/maps/place/Nagoya+University（2021/8/25)

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

The Nobel Prize in Physics 2014

Isamu Akasaki

Prize share: 1/3

Hiroshi Amano

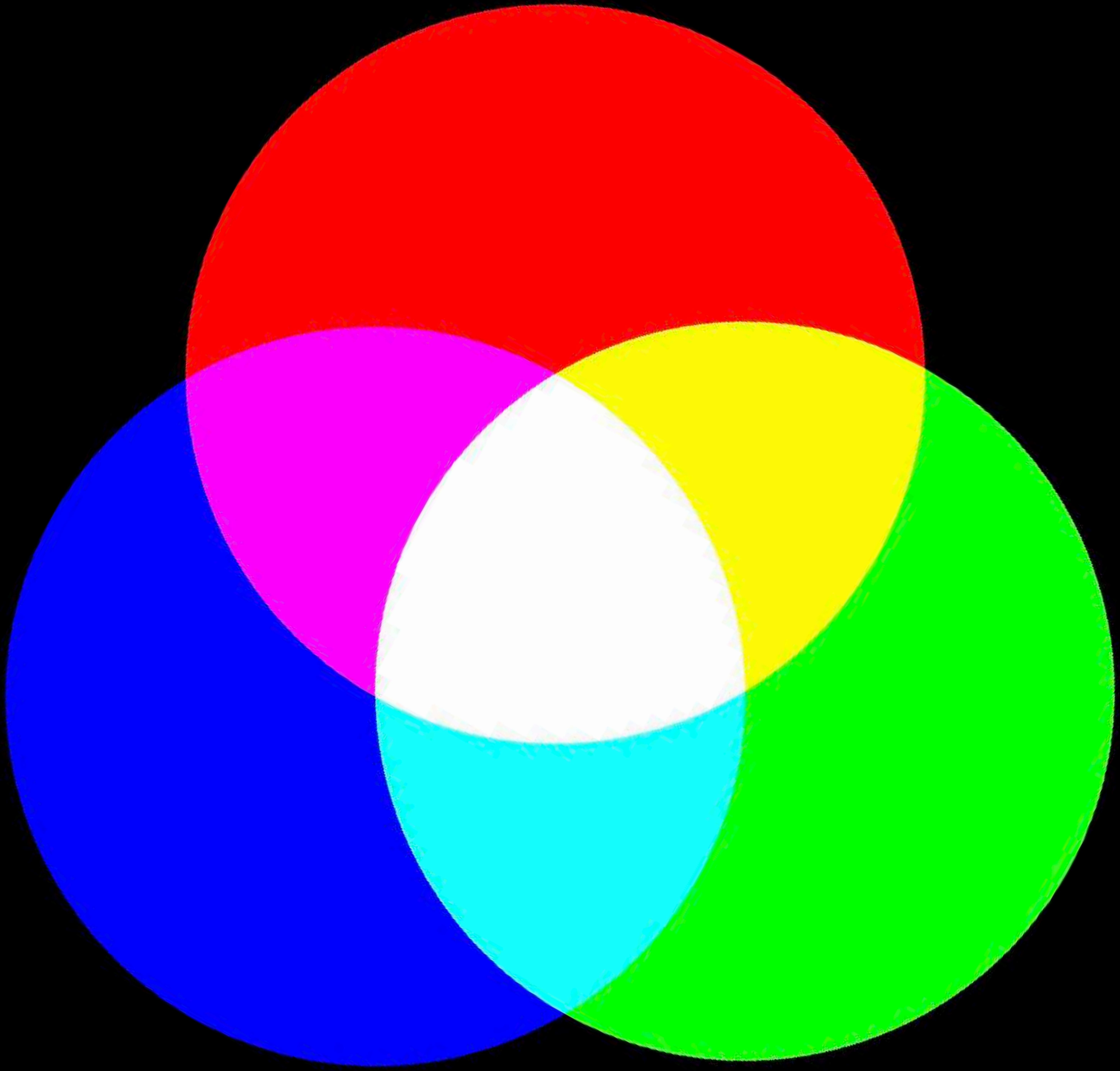
Prize share: 1/3

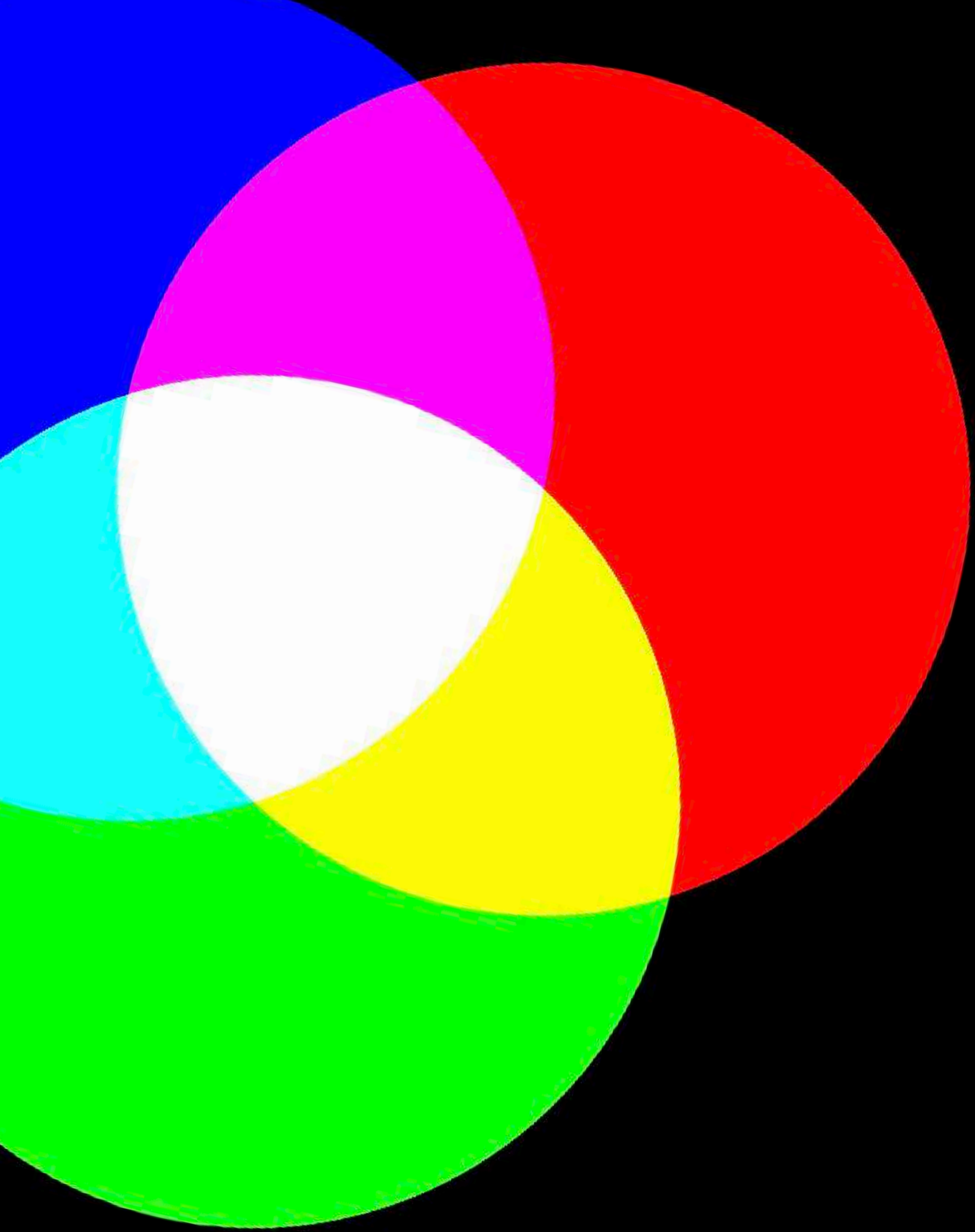
Shuji Nakamura

Prize share: 1/3

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources."

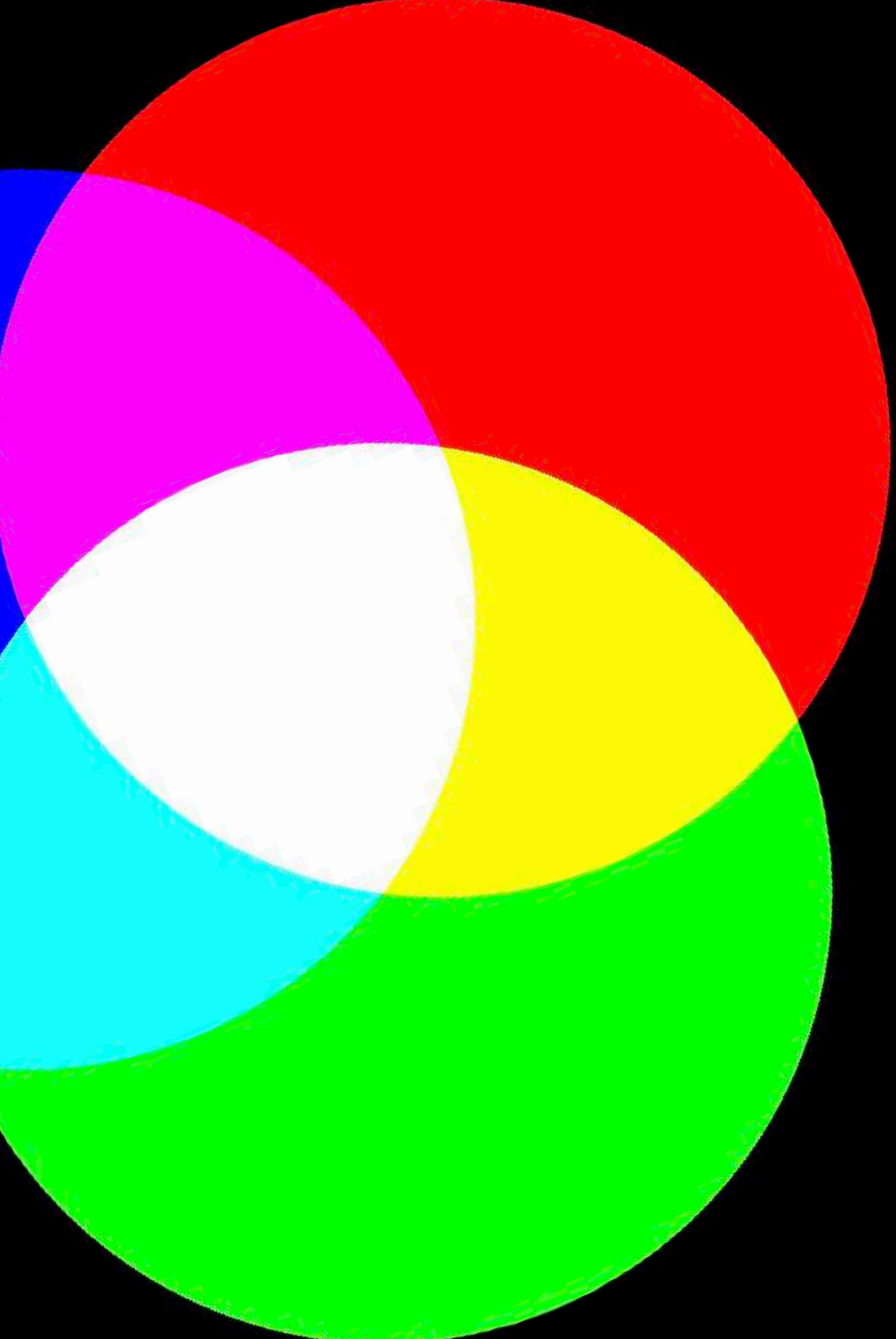
MLA style: The Nobel Prize in Physics 2014. NobelPrize.org. Nobel Prize Outreach AB 2021. Thu. 2 Sep 2021. <https://www.nobelprize.org/prizes/physics/2014/summary/>





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

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

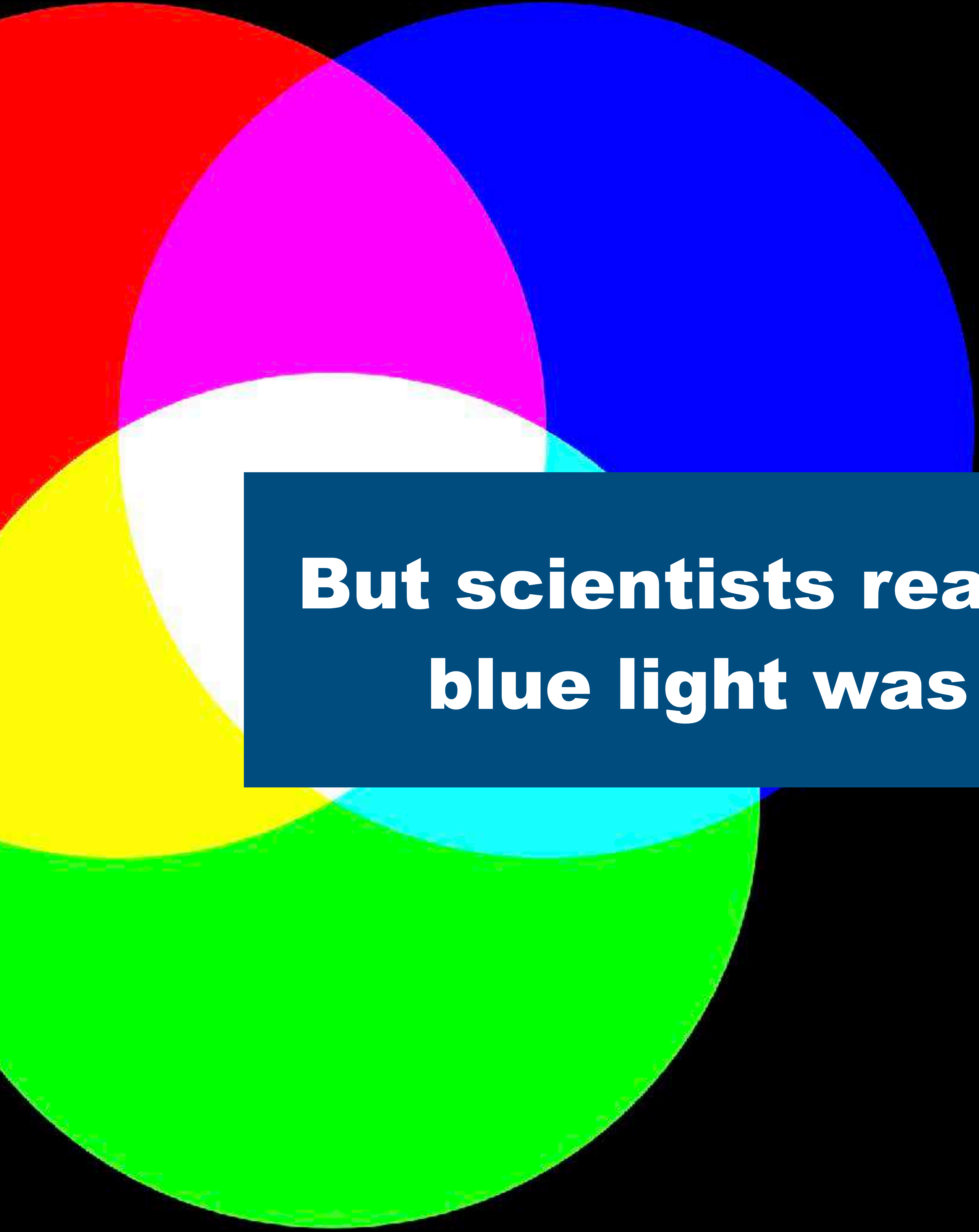


1961 Robert Biard and Gary Pittman (TI) invented an infra-red LED.

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

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

1980s Ultra-bright 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.

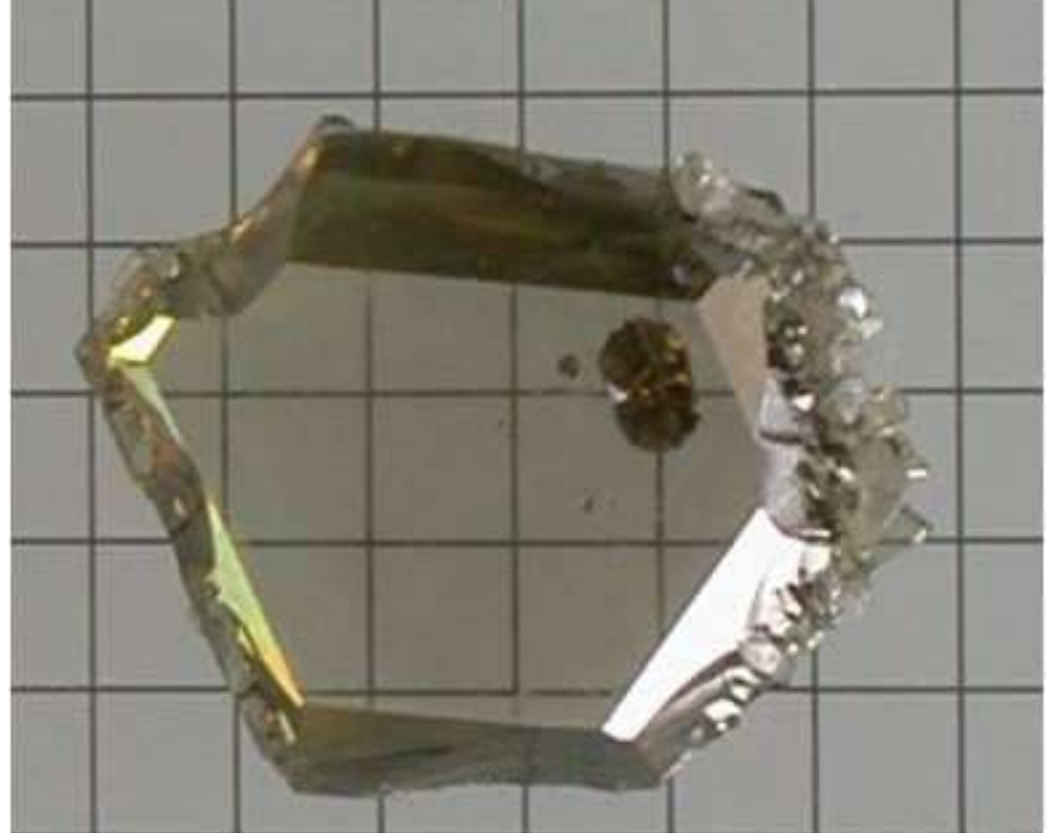
But scientists realized that the emission of blue light was considerably difficult.

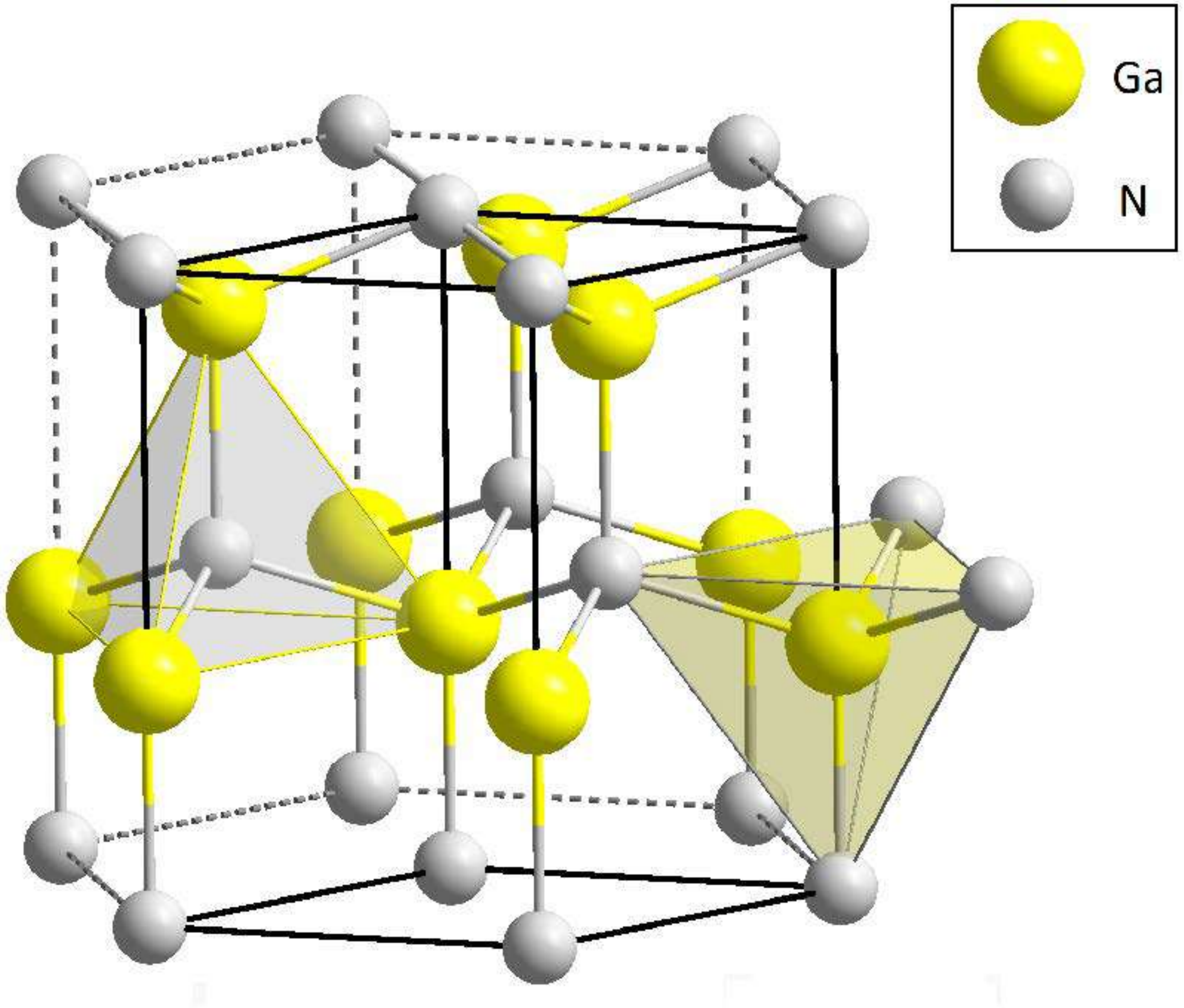
LEDs that emit a pale green light.

1980s Ultra-bright 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

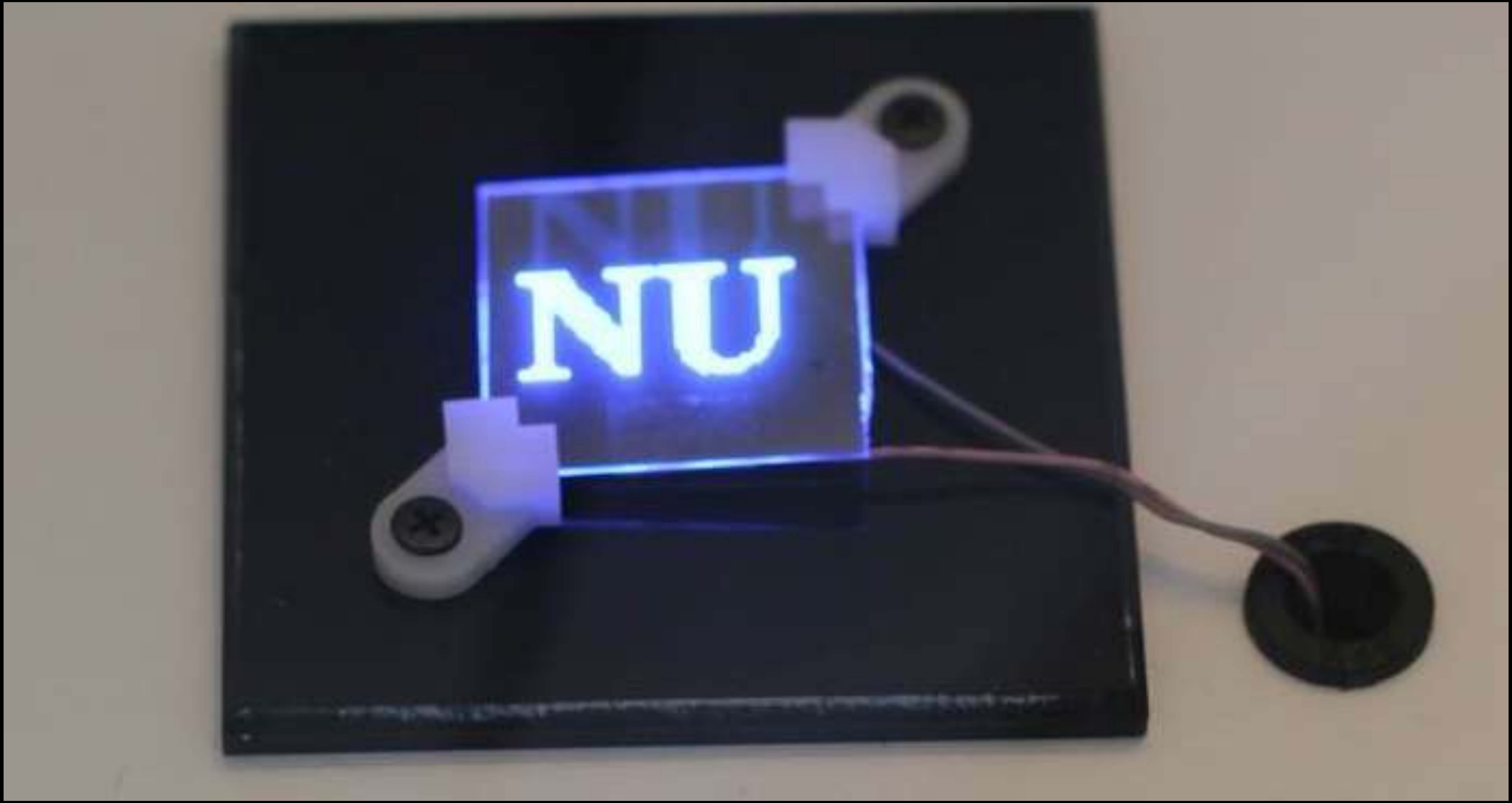
1952	Graduated from the School of Science, Kyoto University Began working at Kobe Kogyo Corporation
1959	Research Associate, School of Engineering, Nagoya University
1964	Lecturer, School of Engineering, Nagoya University
1964	Received Doctorate of Engineering, School of Engineering, Nagoya University
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)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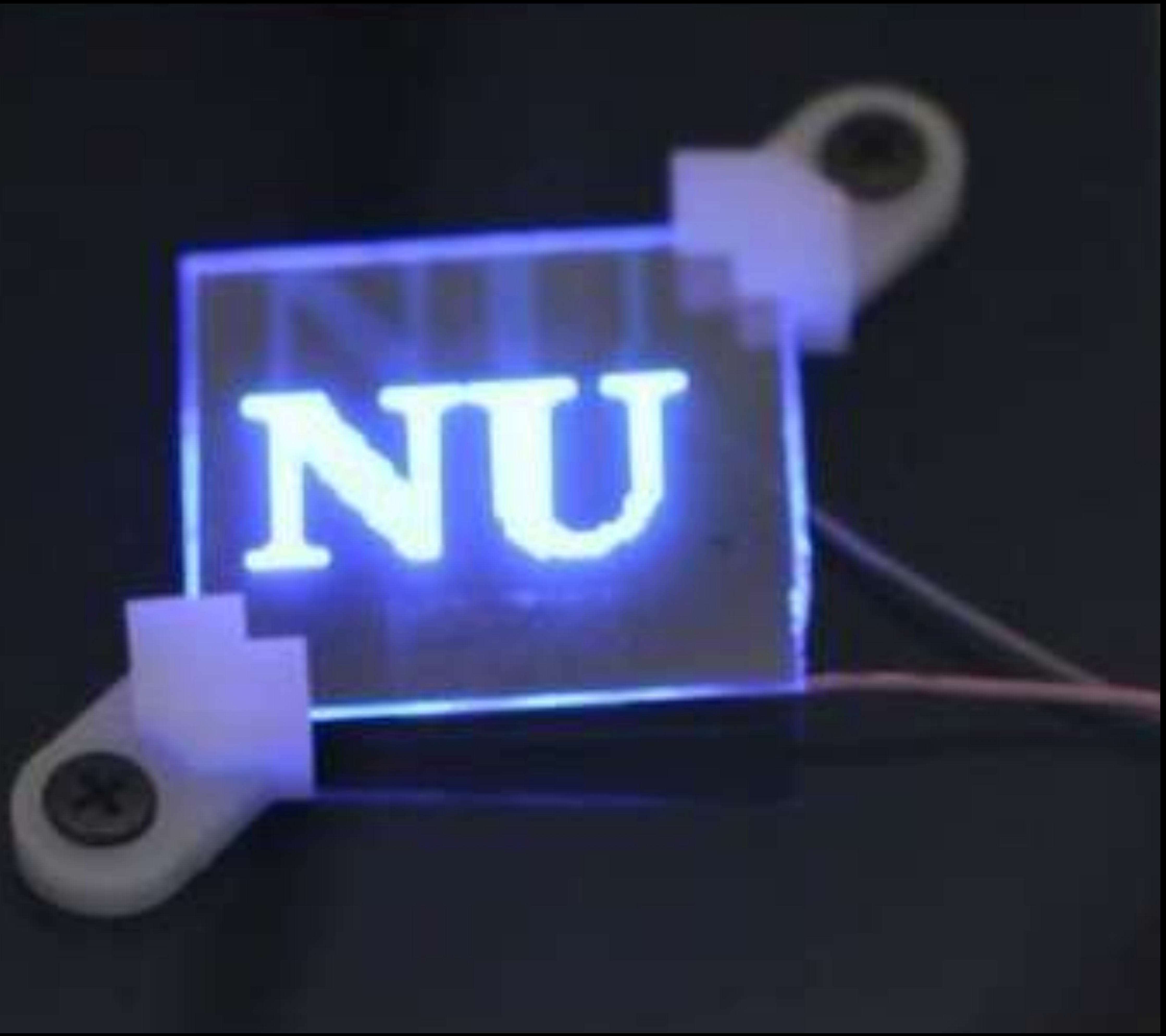


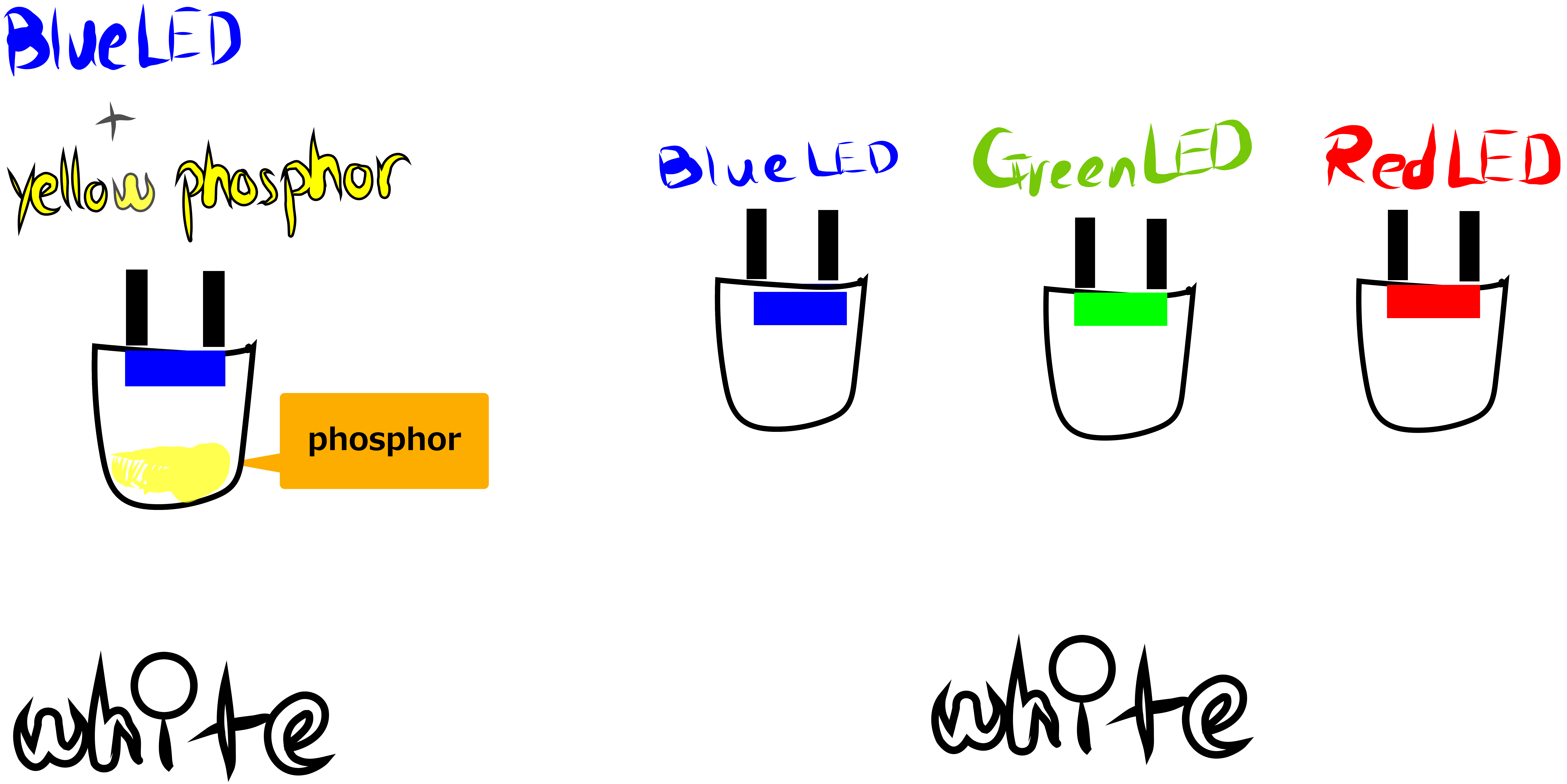
1986 Profs. Akasaki and Amano were the first to create a high-quality GaN crystal.

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

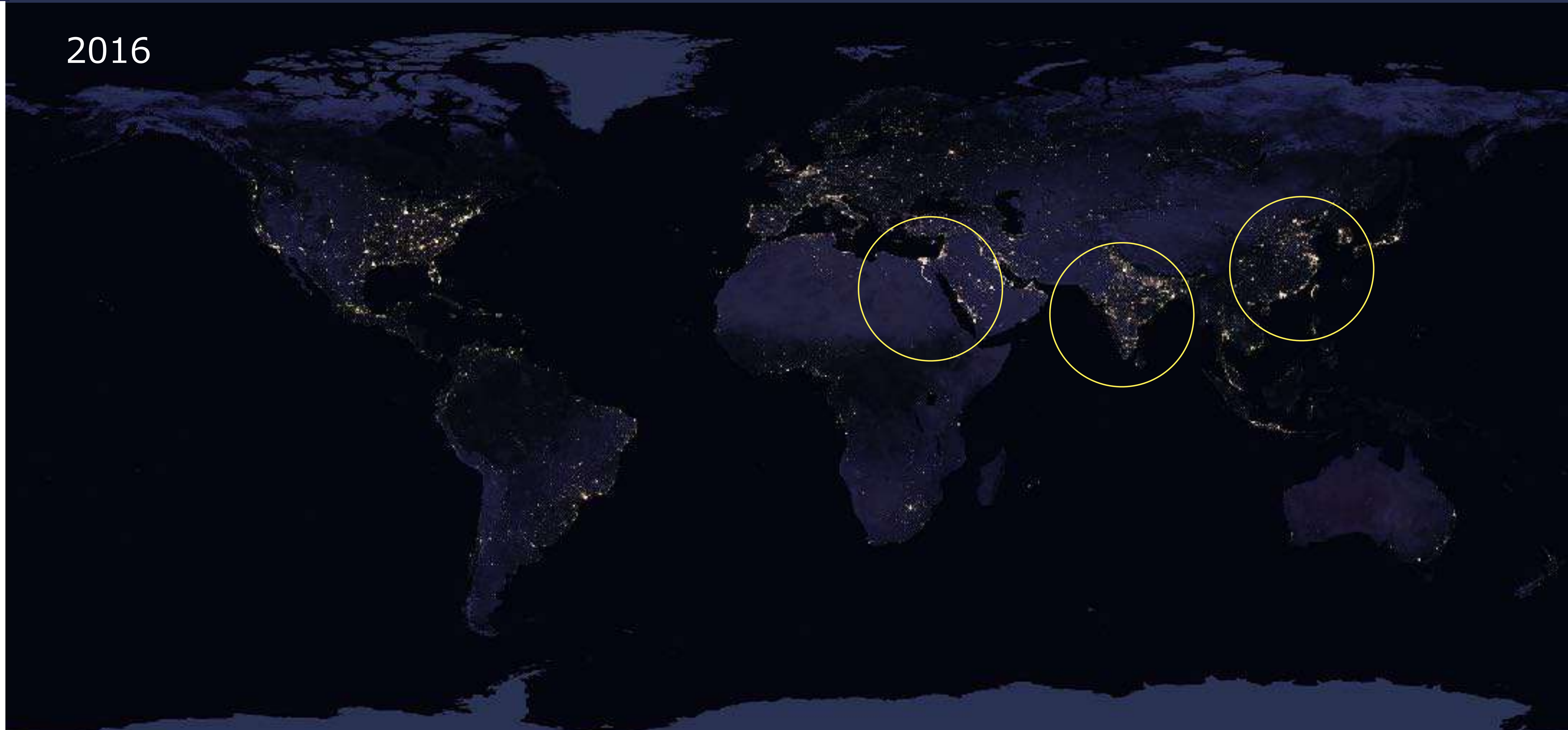
White light source implementation



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.

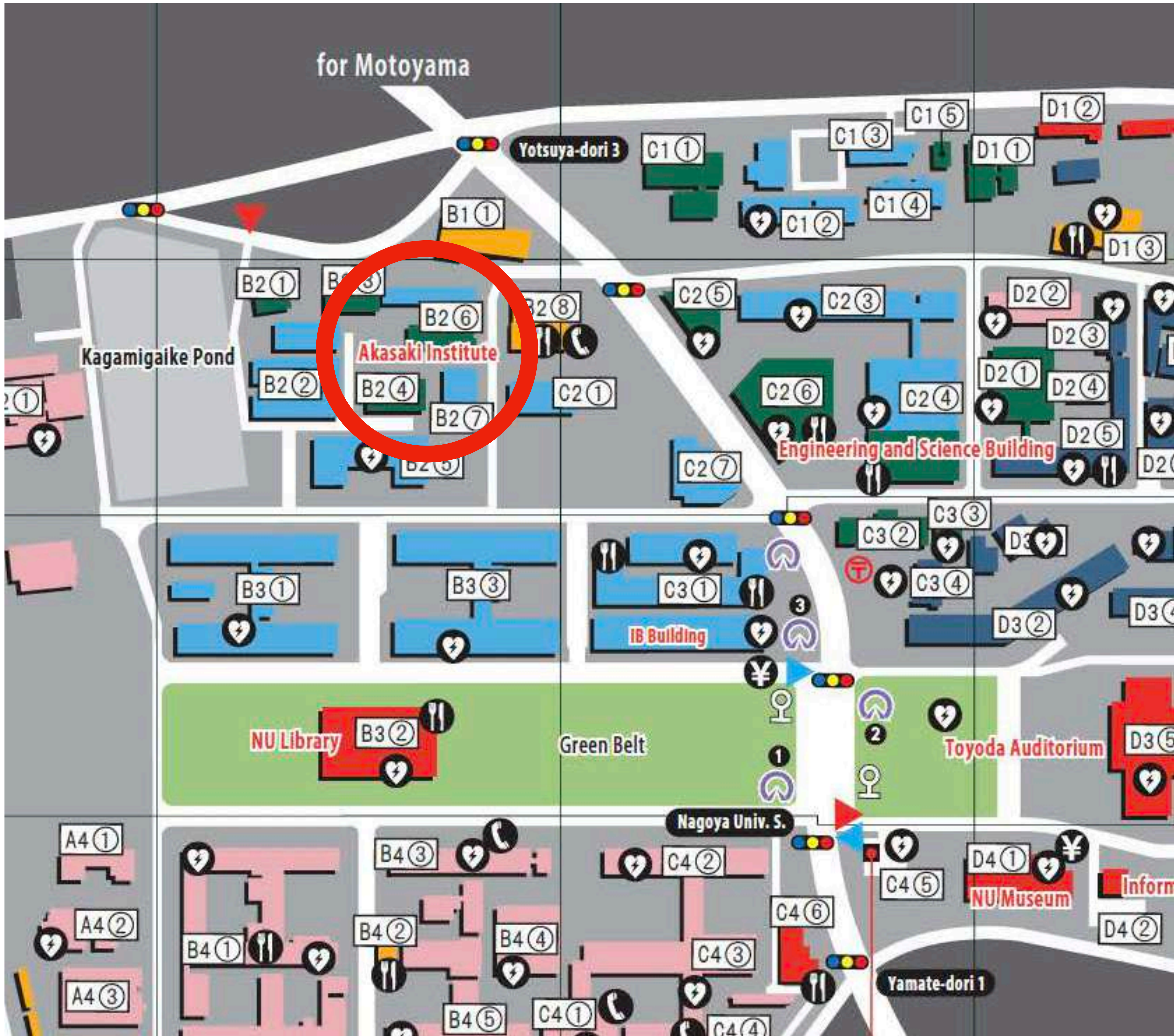


https://earthobservatory.nasa.gov/features/NightLights/page3.php (2021/9/3)

Akasaki Institute

https://www.aip.nagoya-u.ac.jp/en/extramural/akasaki_institute/index.html

- Open weekdays (excluding national holidays)
  - 10:00 - 16:00
- Admission to the Exhibition Room on the first floor is free.



Q1

What is the name of the material used to manufacture blue LED?

Light emitting data (LED)

Visible Light Communication (VLC)

1998　Proposed by Prof. Masao Nakagawa, Keio University

2001　Visible Light Communication Consortium

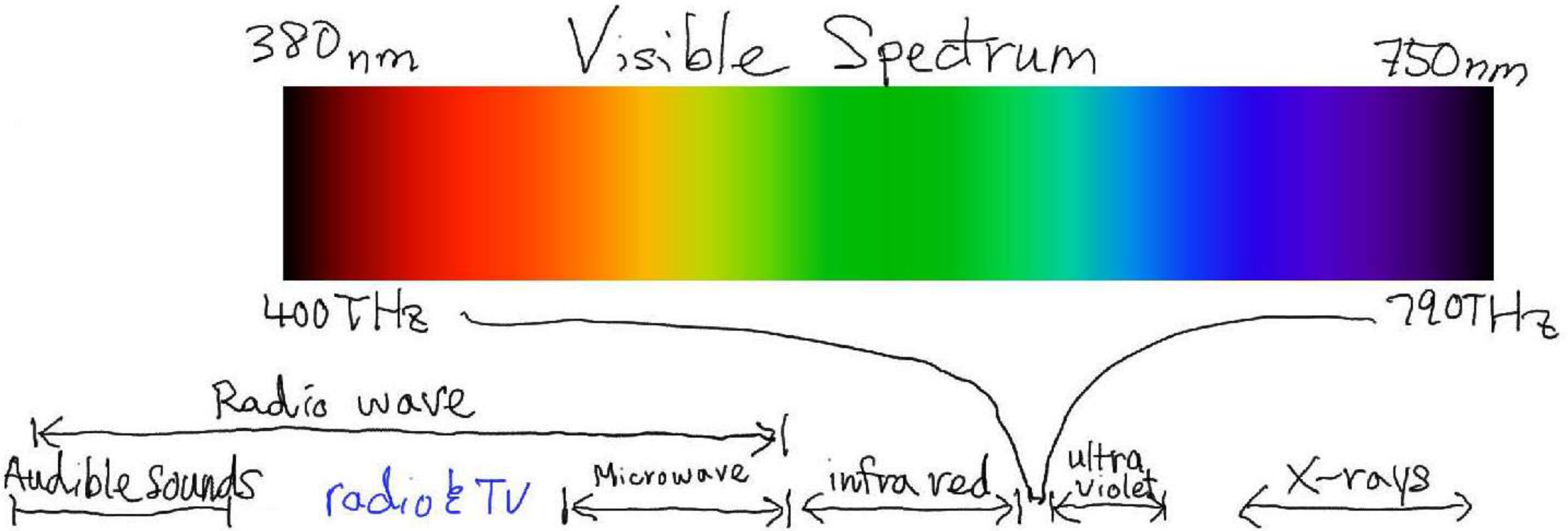
(Chair：Prof. Shinichiro Haruyama, Keio University)

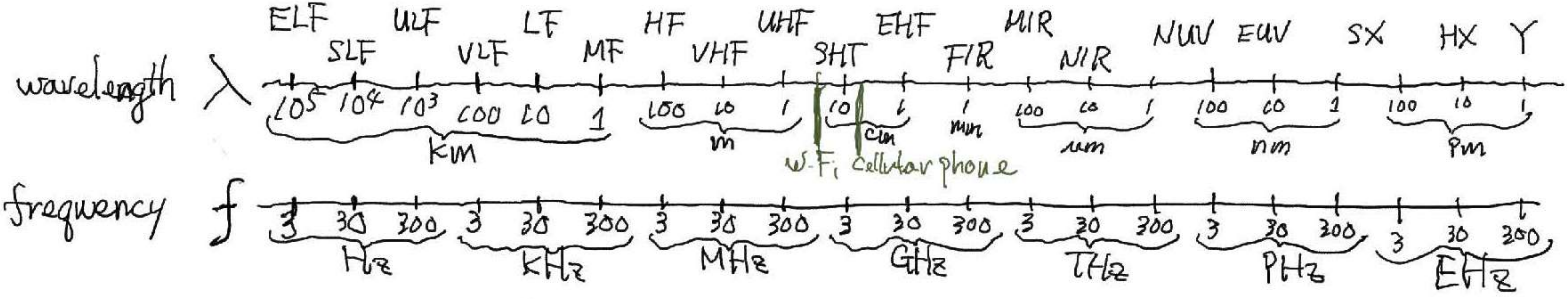
2014　Visible Light Communications Association

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

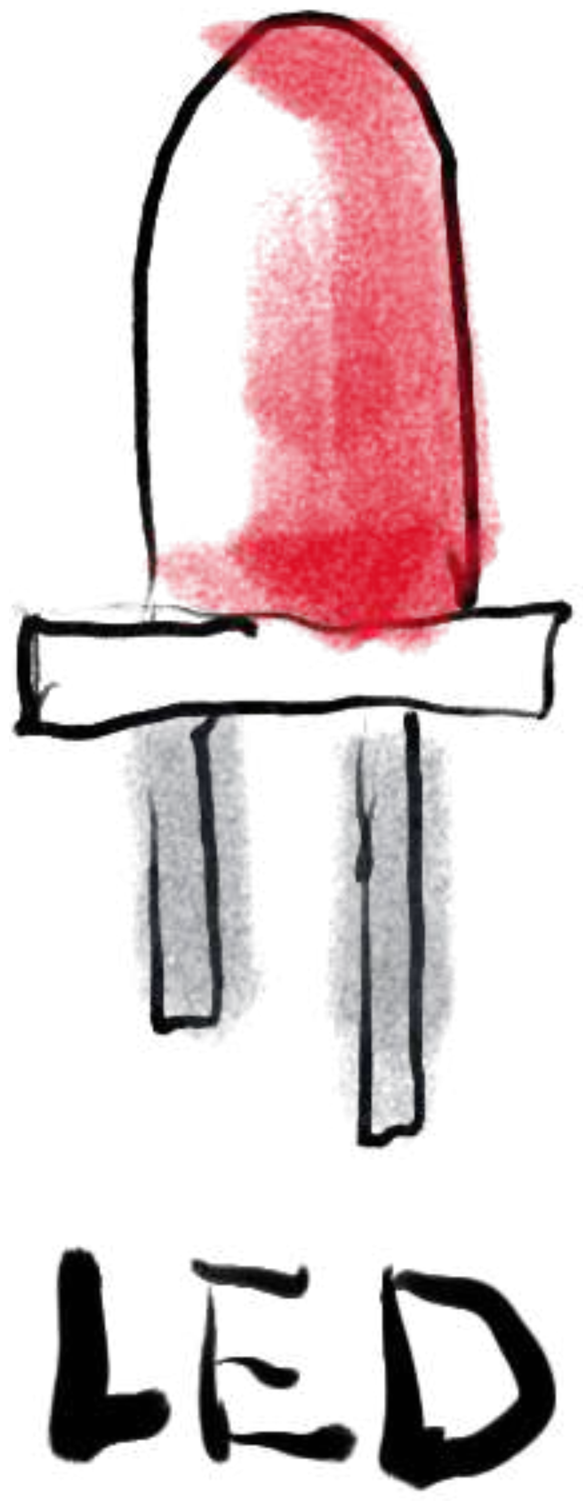
	Class	Wavelength λ	Frequency f
γ	Gamma rays	1 pm	300 EHz
HX	Hard X-rays	10 pm	30 EHz
SX	Soft X-rays	100 pm	3 EHz
		1 nm	300 PHz
EUV	Extreme ultraviolet	10 nm	30 PHz
NUV	Near ultraviolet, visible	100 nm	3 PHz
		1 µm	300 THz
NIR	Near infrared	10 µm	30 THz
MIR	Mid infrared	100 µm	3 THz
FIR	Far infrared	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

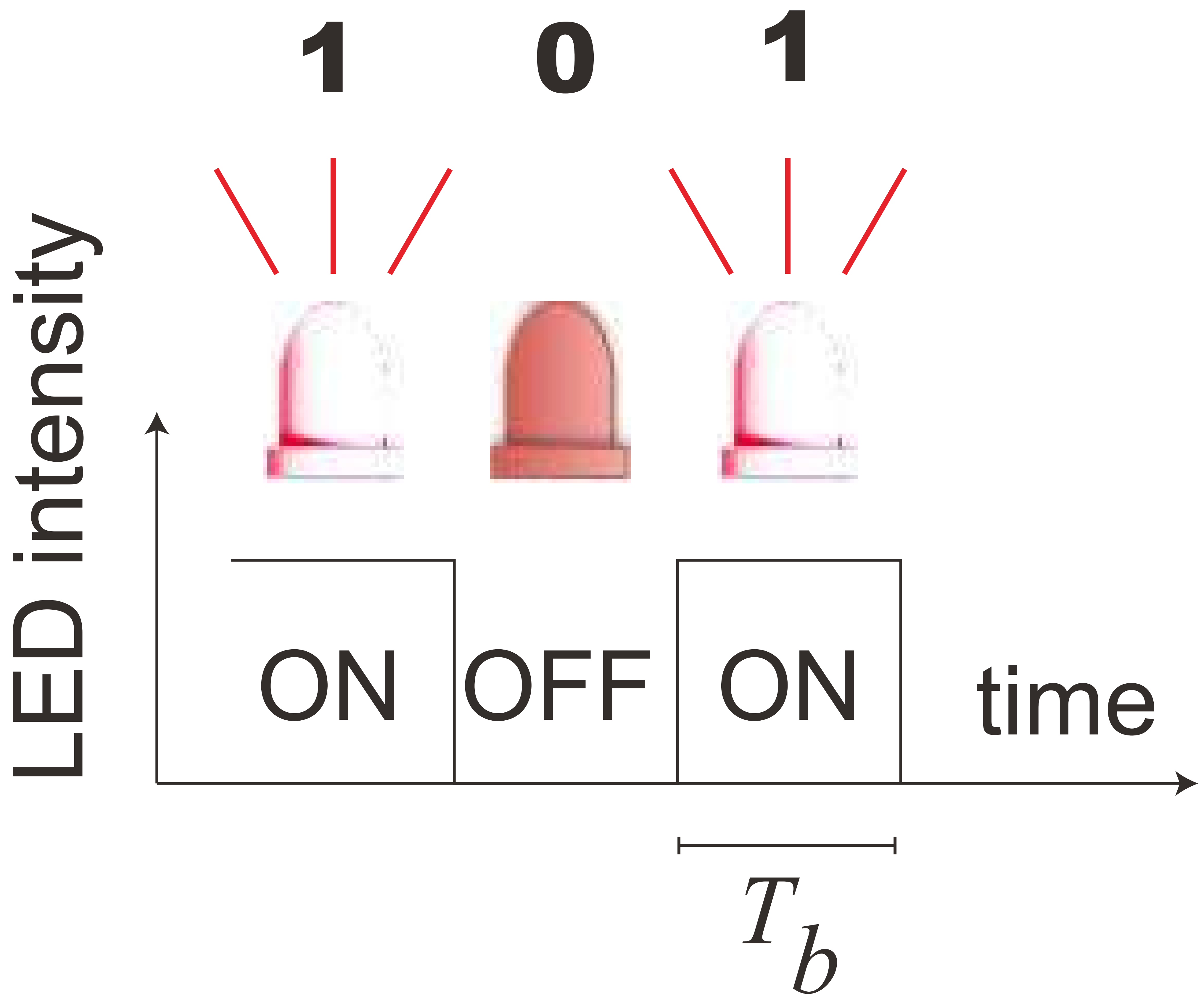
In most cases, VLC uses LEDs for a transmitter.



- 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)

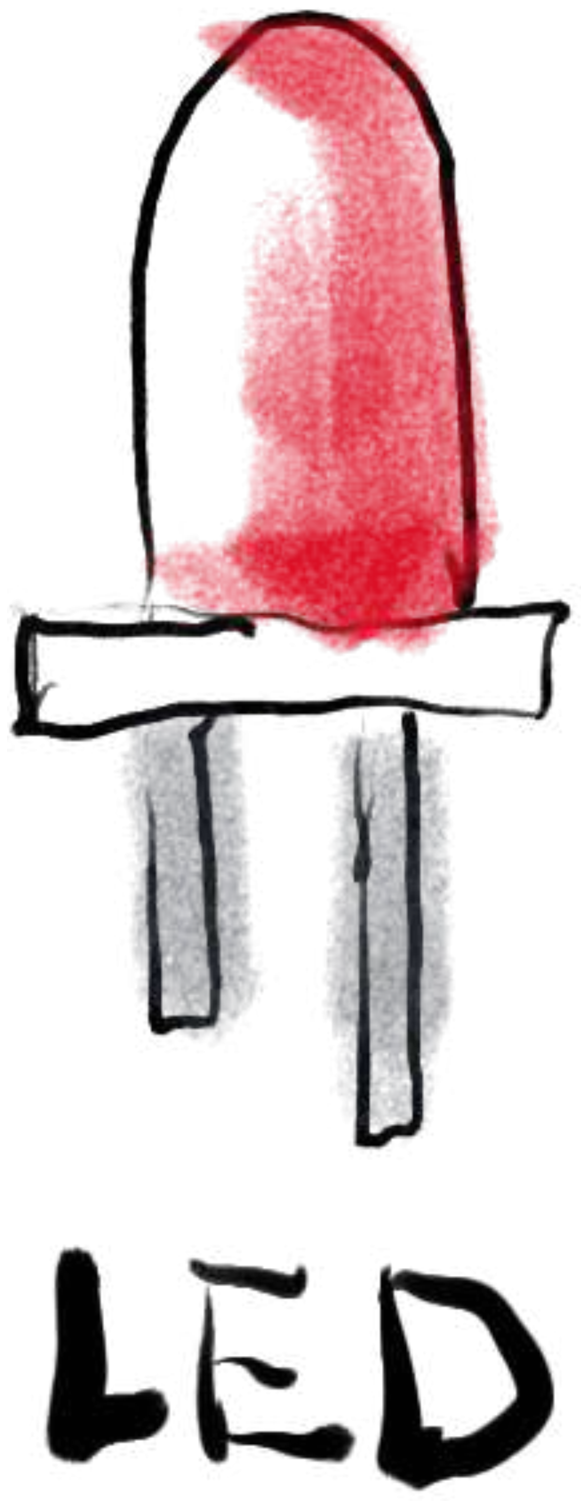
The simplest form of modulation

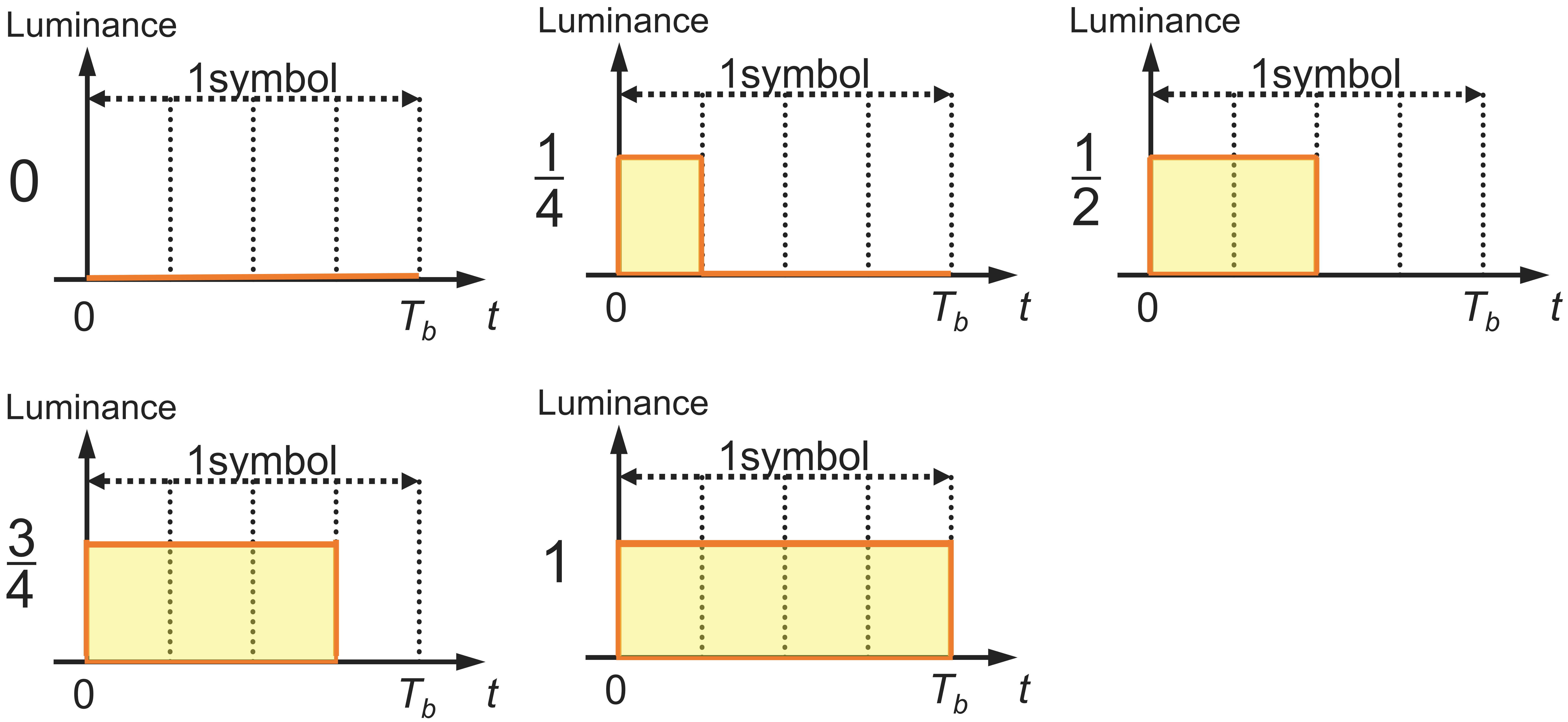


Data rate is $R_b = 1/T_b$

Pulse-width modulation (PWM)

The simplest form of modulation





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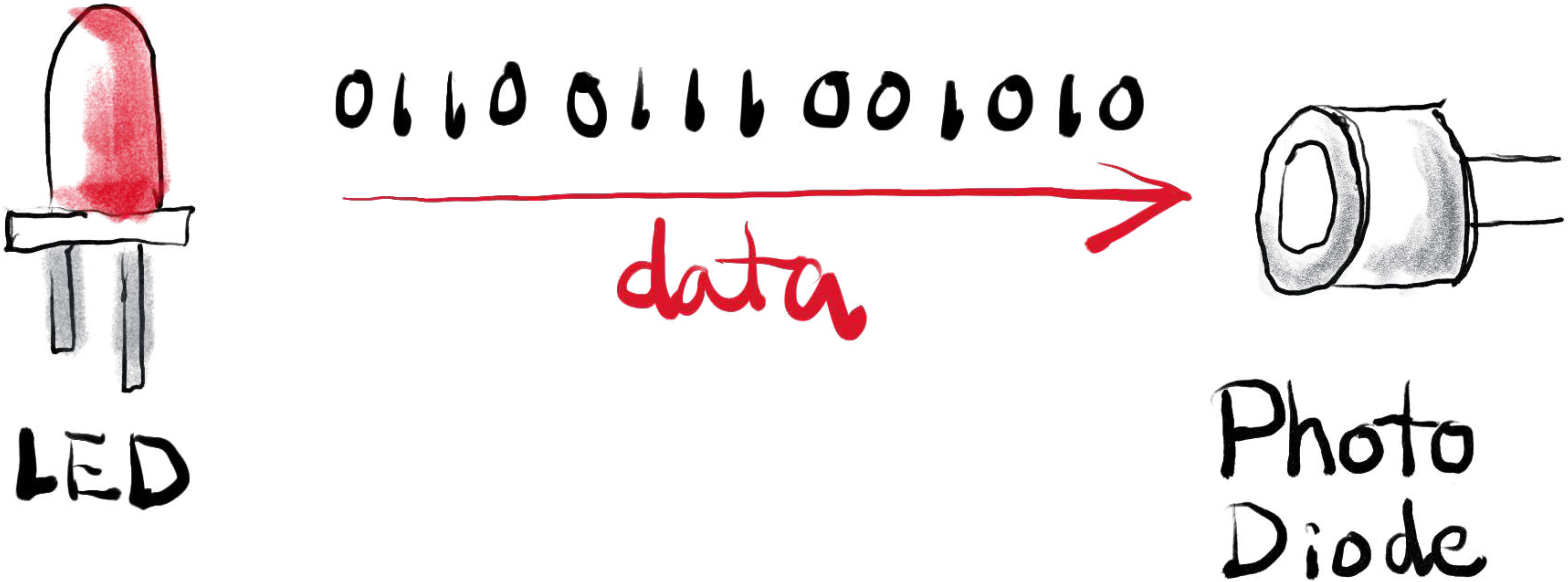
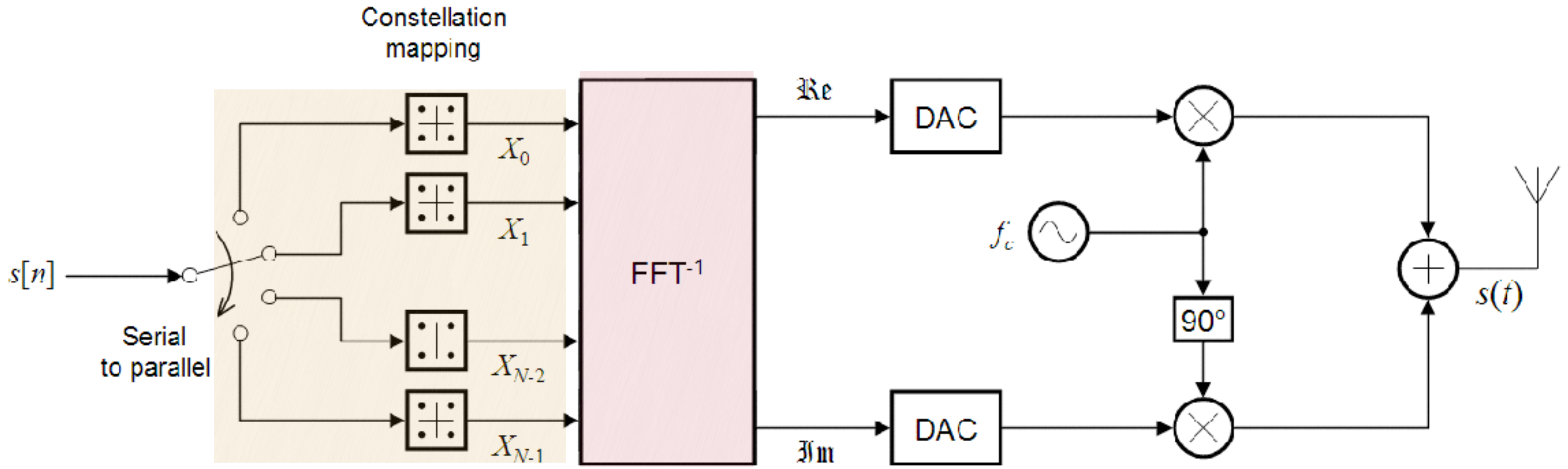


Intensity modulation and direct detection (IM/DD) systems

Optical Orthogonal Frequency Division Multiplexing (optical OFDM)

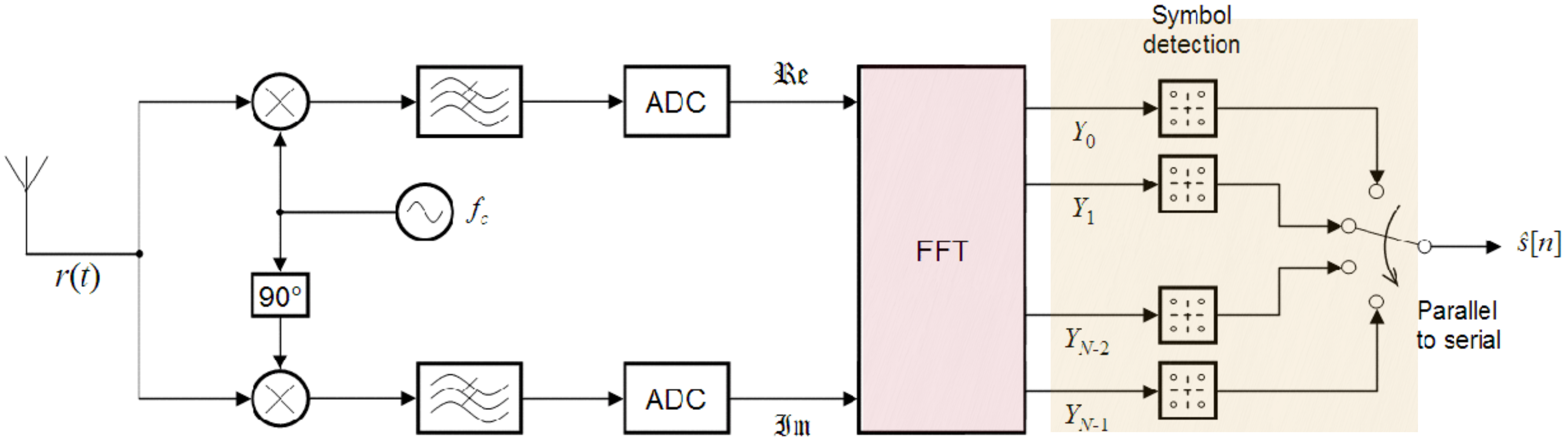
OFDM is the modulation scheme adopted for wireless LAN and 4G, 5G mobile phone.



Multiplexing (parallel transmission)

Convert signal to frequency domain

Frequency division multiplexing



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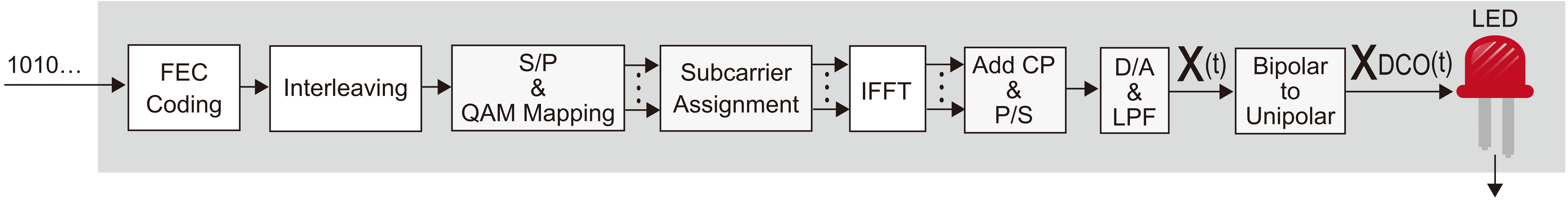
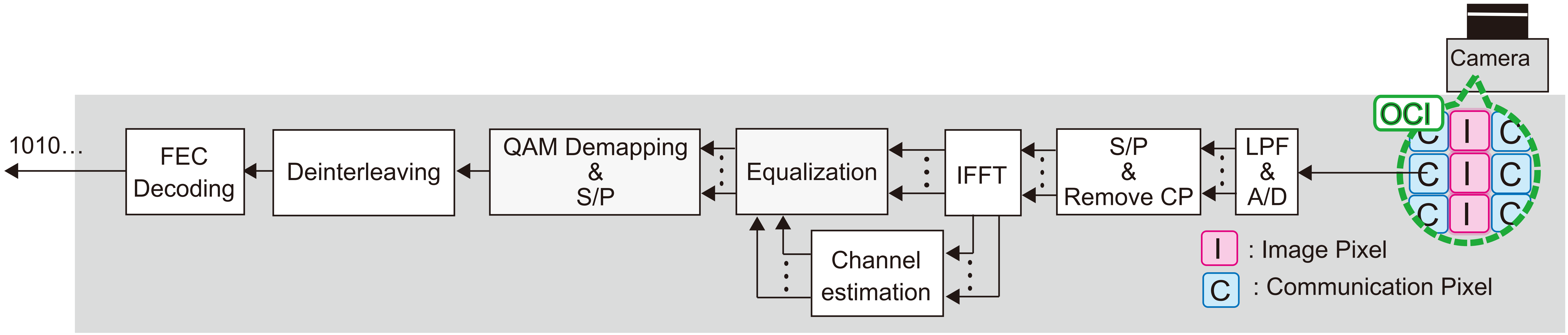
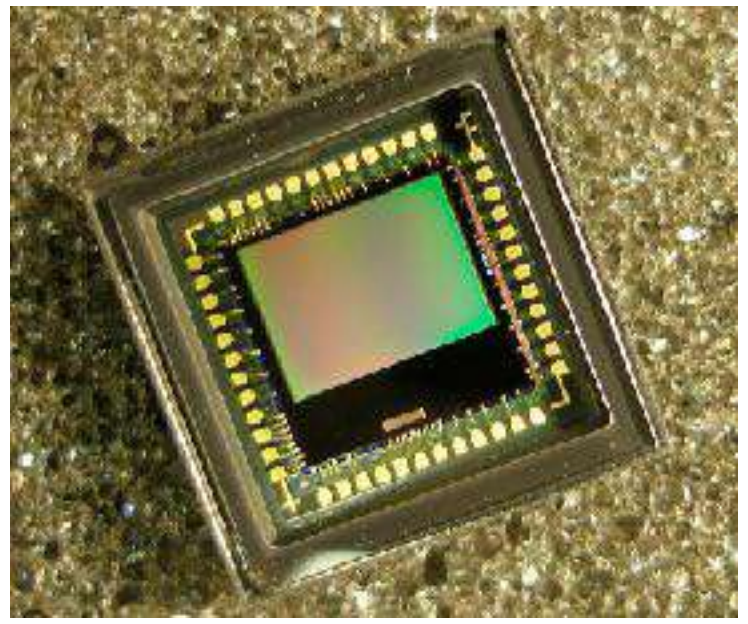


Direct-current-biased optical orthogonal frequency division multiplexing (DCO-OFDM)

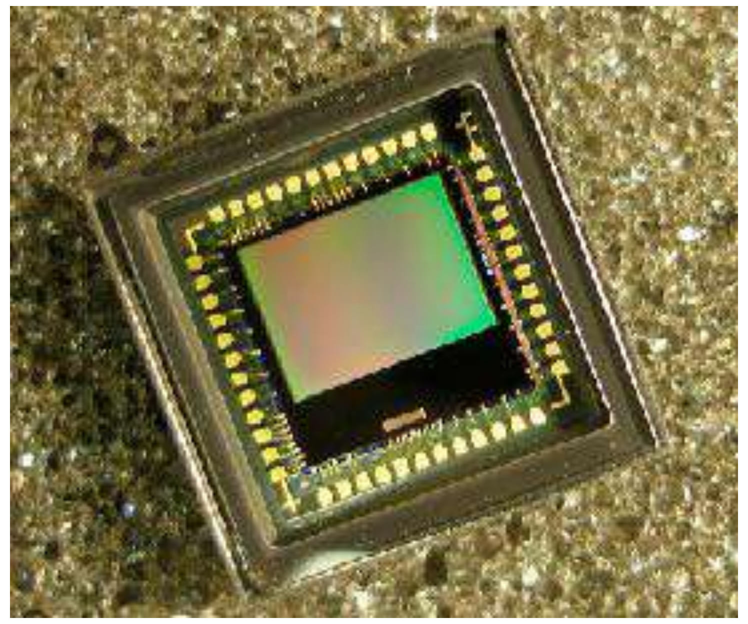




https://en.wikipedia.org/wiki/Active-pixel_sensor

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

CMOS (complementary metal oxide semiconductor)



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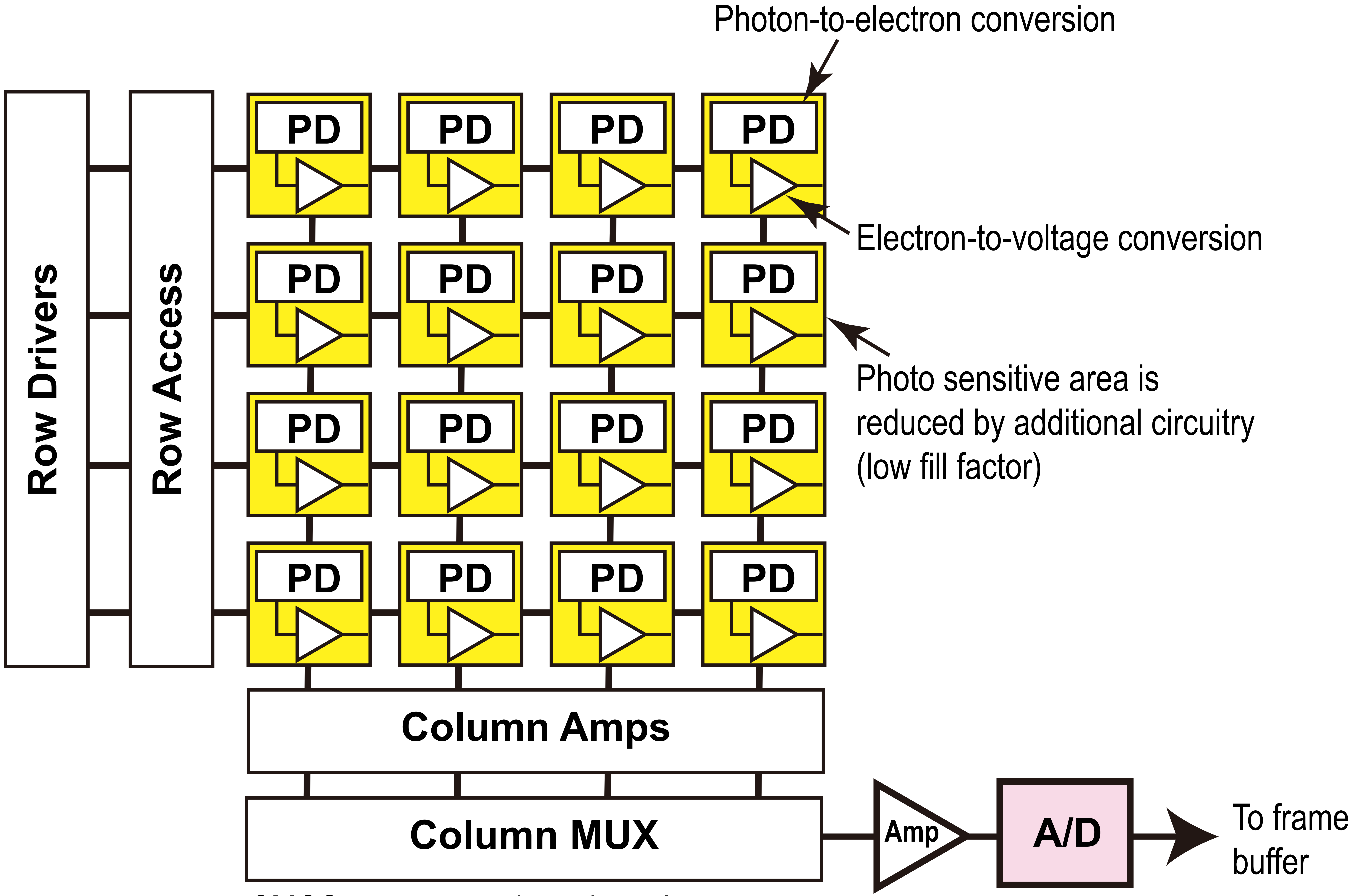


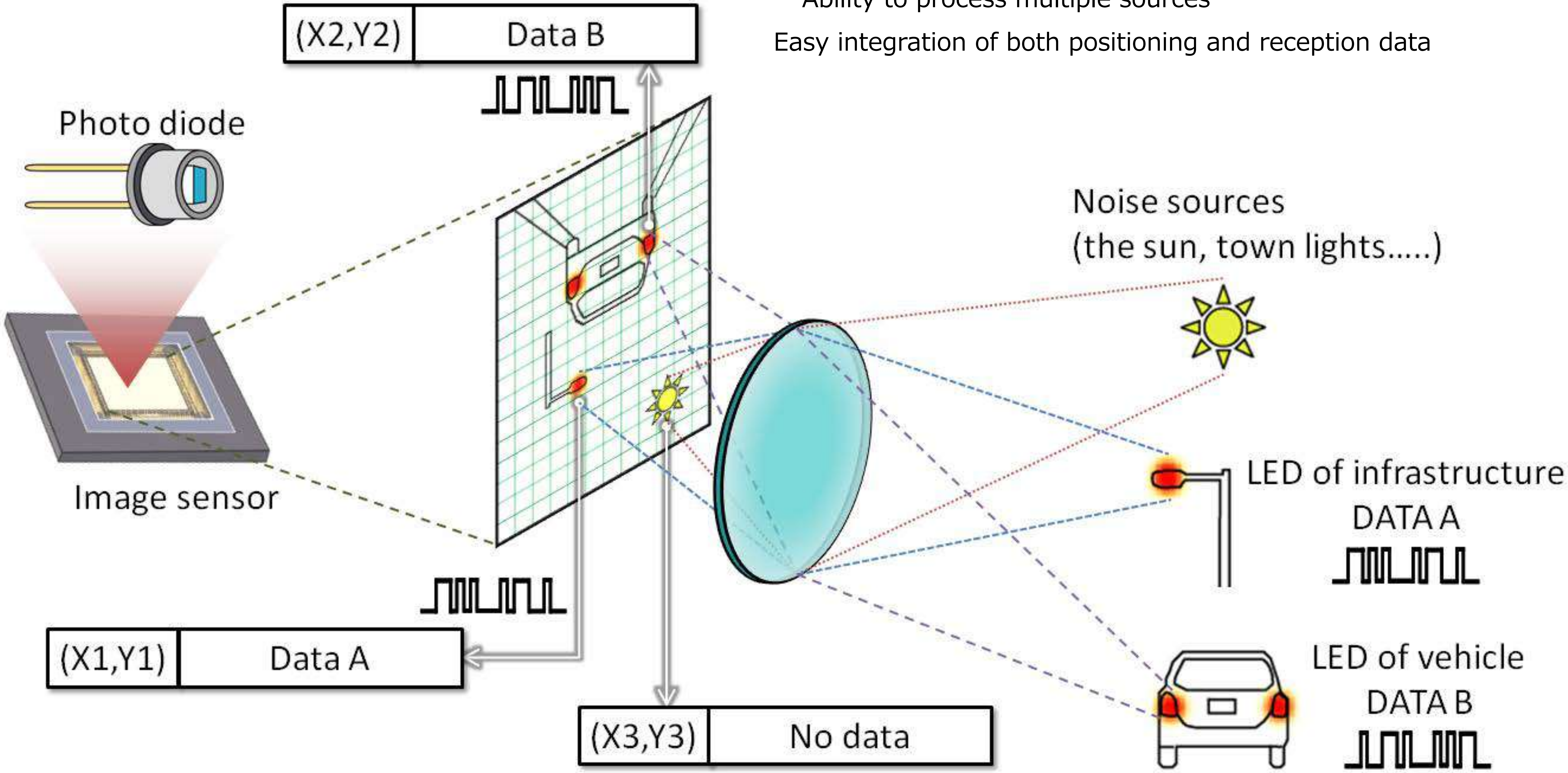
CMOS sensors read out the voltage using row and column decoders, like a digital memory.

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

Spatial separation of sources

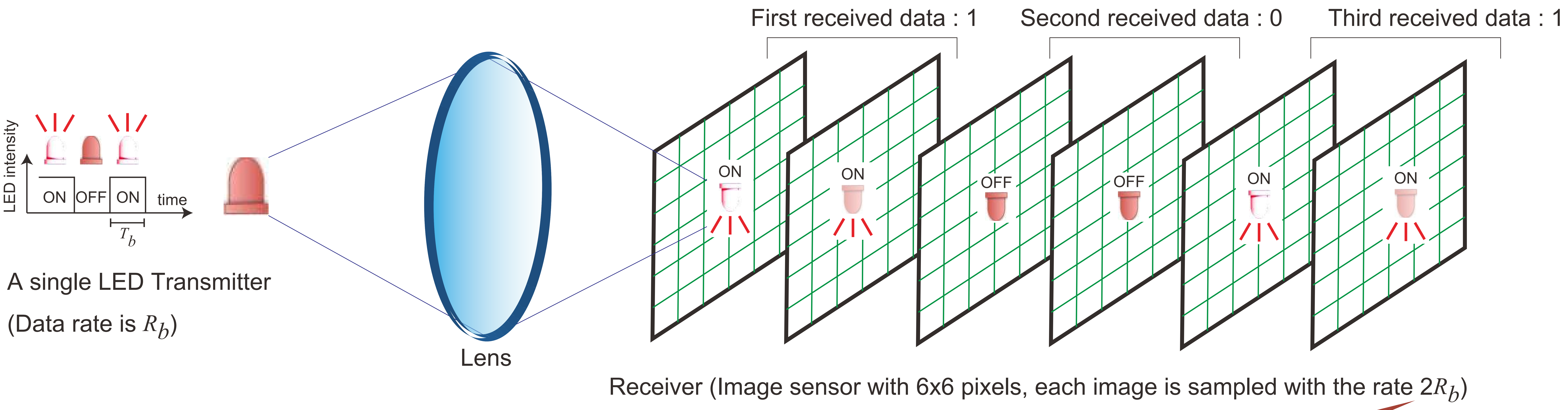
Ability to process multiple sources

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.

Sampling of images

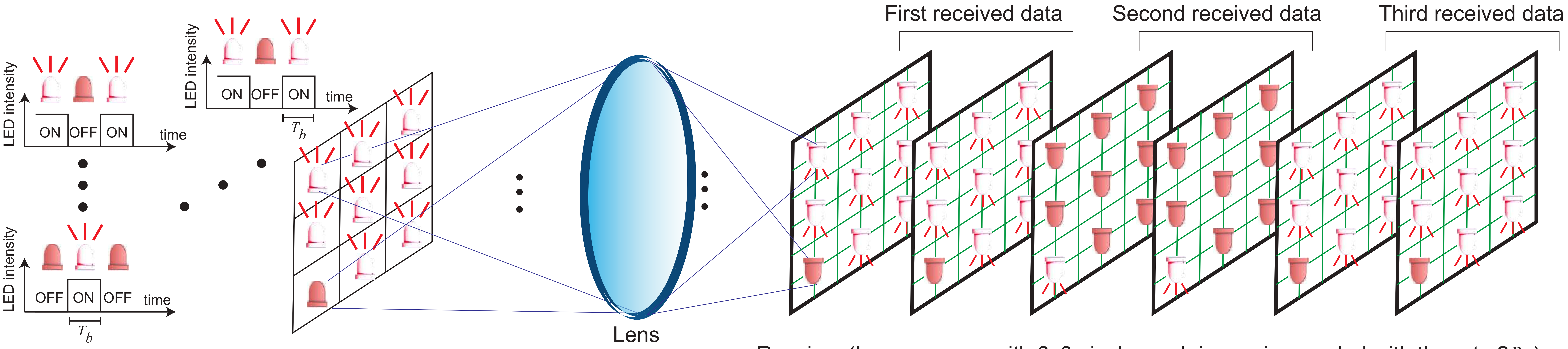


$Data\ Rate \leq Sampling\ Rate$

- Nyquist Sampling theorem

A signal can be reconstructed from its samples if the original signal has no frequencies above 1/2 the sampling frequency.

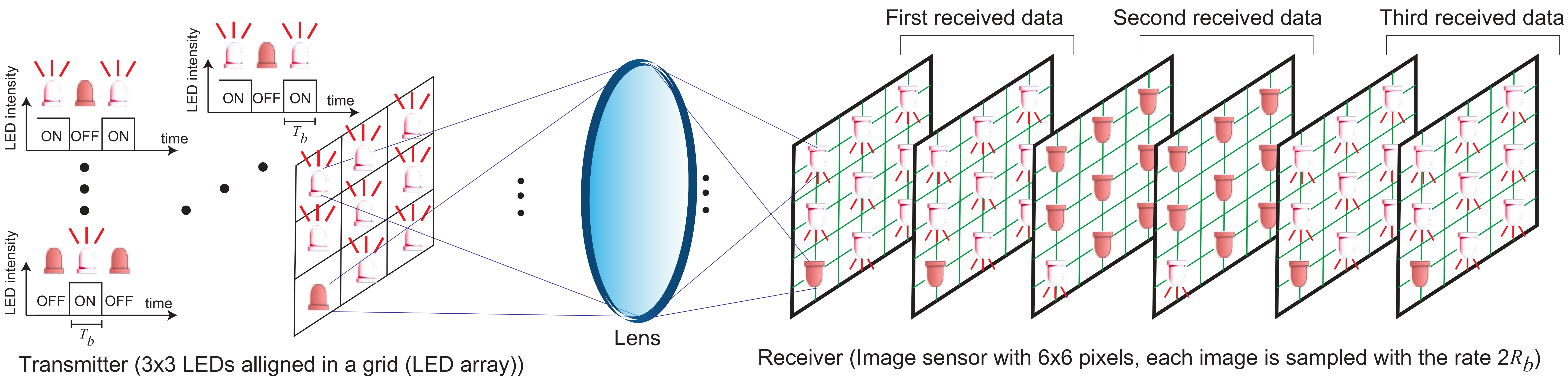
LED array transmitter and Image sensor receiver



Transmitter (3x3 LEDs alligned in a grid (LED array))
Receiver (Image sensor with 6x6 pixels, each image is sampled with the rate $2R_b$)

- Spatial separation

  Image sensor receiver can receive and process multiple transmitting sources.


LED intensity
ON
OFF
ON
time
LED intensity
ON
OFF
ON
time
T_b
LED intensity
OFF
ON
OFF
time
T_b
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 $2R_b$)

Q2

If the source data rate is 120Hz, what is the minimum sampling rate to reconstruct original data?

VLC using high-speed camera

High-speed camera

iPhone 12

Slo-mo video at 240 fps

Edited to 960 fps

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

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

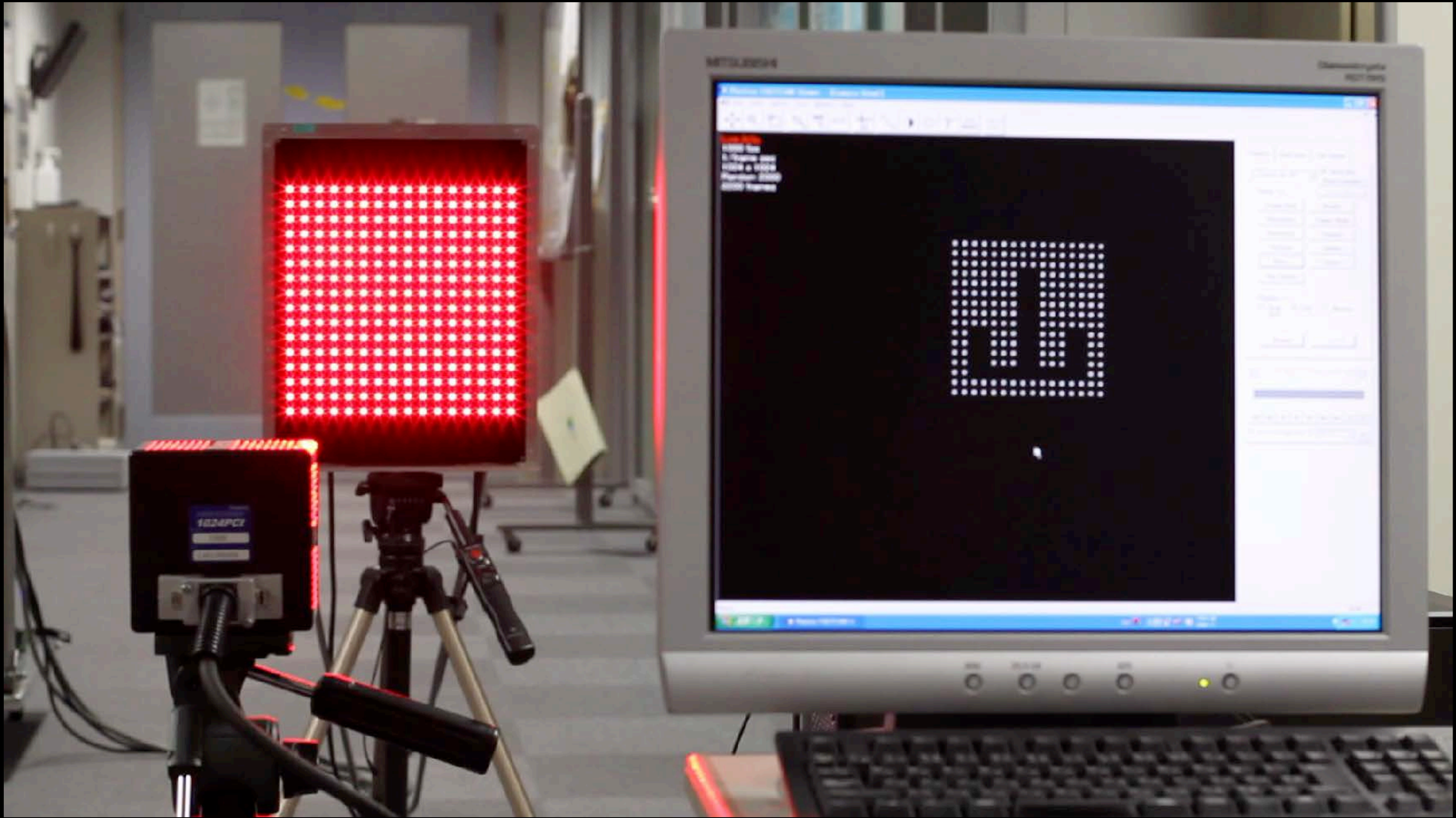
Considering Nyquist sampling (1/2)

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

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

LED array: 500 Hz

High-speed camera: 1000 fps



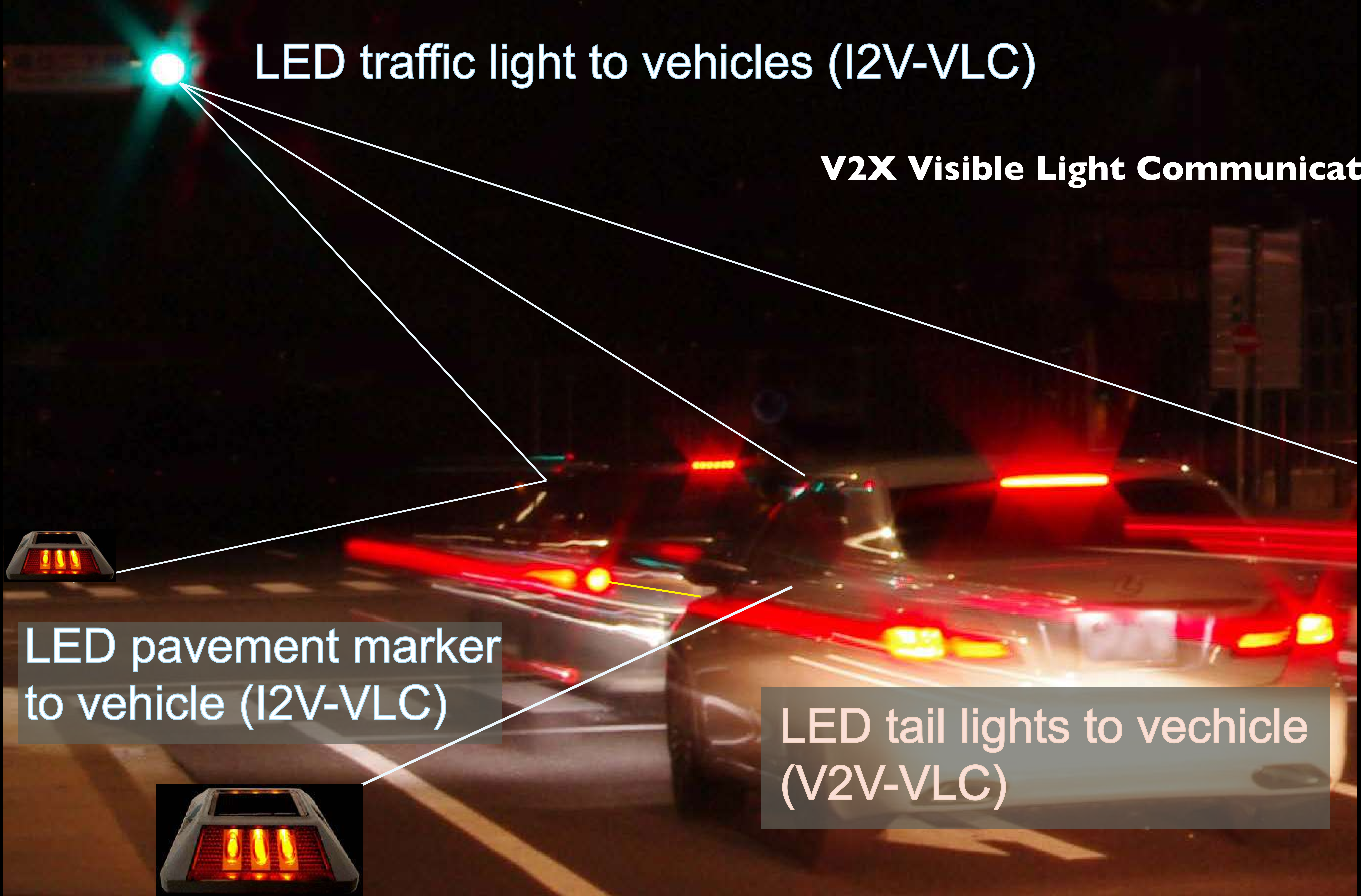
High-speed Image Sensor

160 km/h

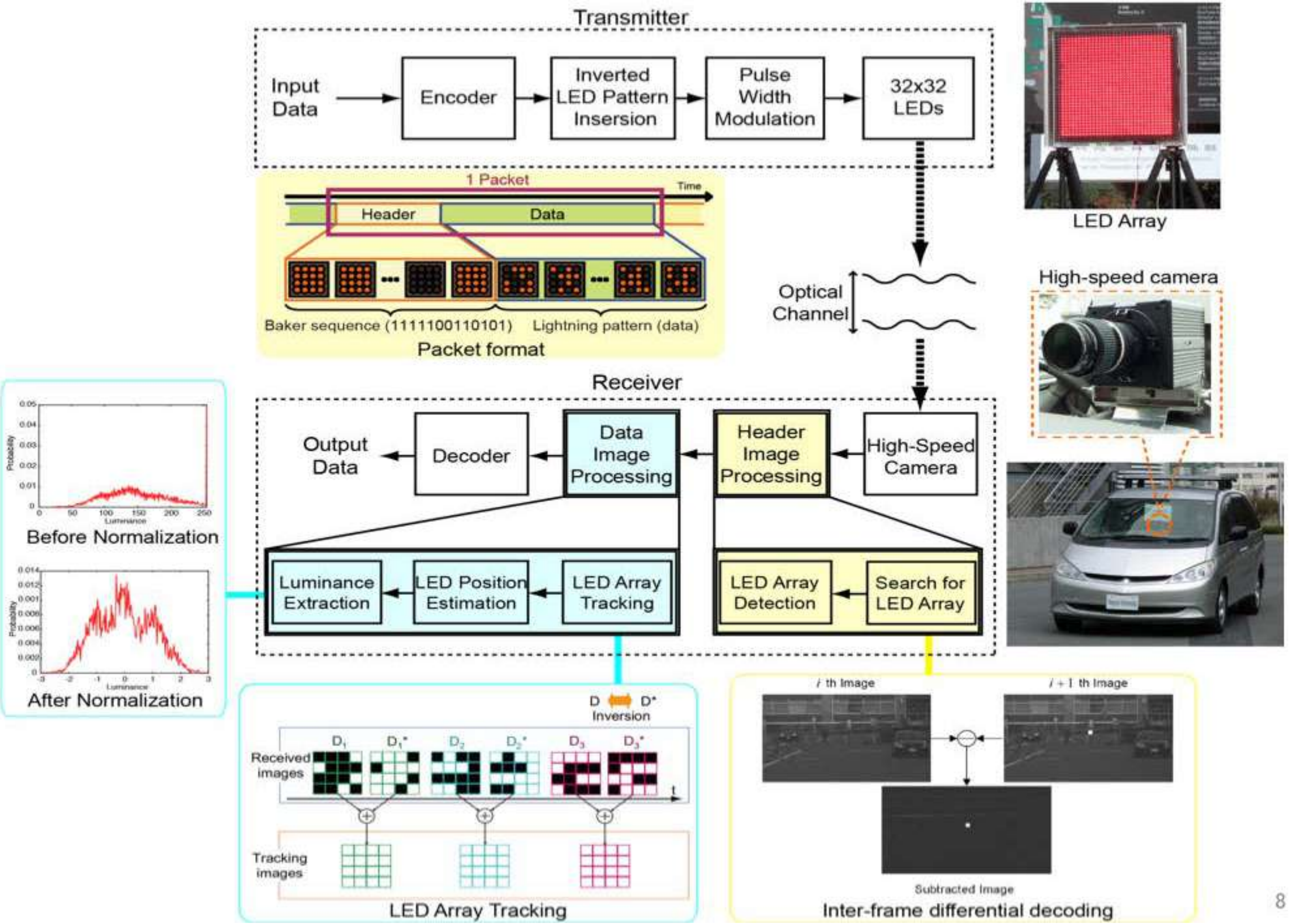
I. Ishii, et al, “High-frame-rate optical flow system,” IEEE Trans. on Circuits and Systems for Video Technology, Jan. 2012.

High-speed image processing for automotive applications


ノンステップバス
27-60

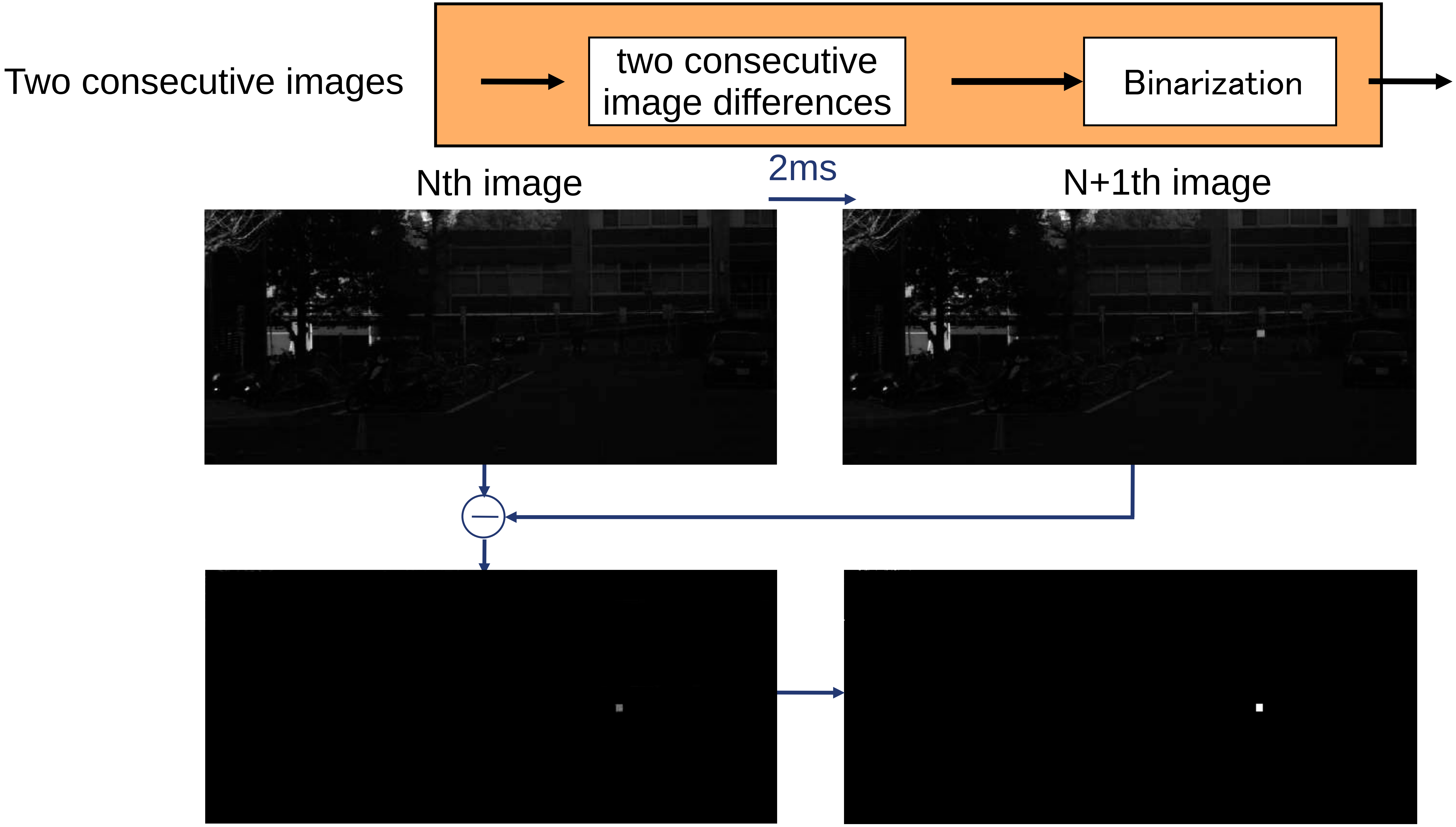

LED traffic light to vehicles (I2V-VLC)
V2X Visible Light Communication
LED pavement marker
to vehicle (I2V-VLC)
LED tail lights to vechicle
(V2V-VLC)

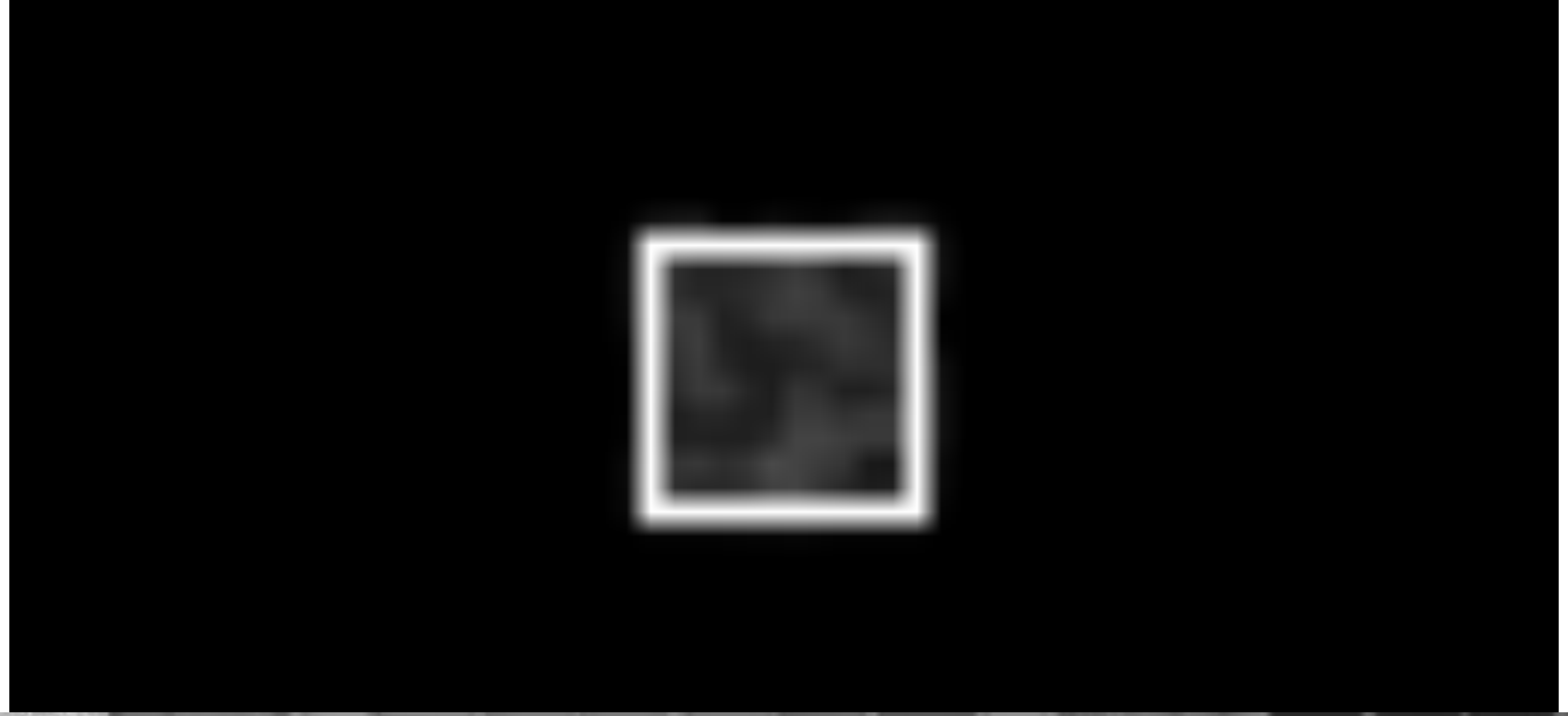
Vehicle-to-Infrastructure Visible Light Communications (V2I-VLC) System

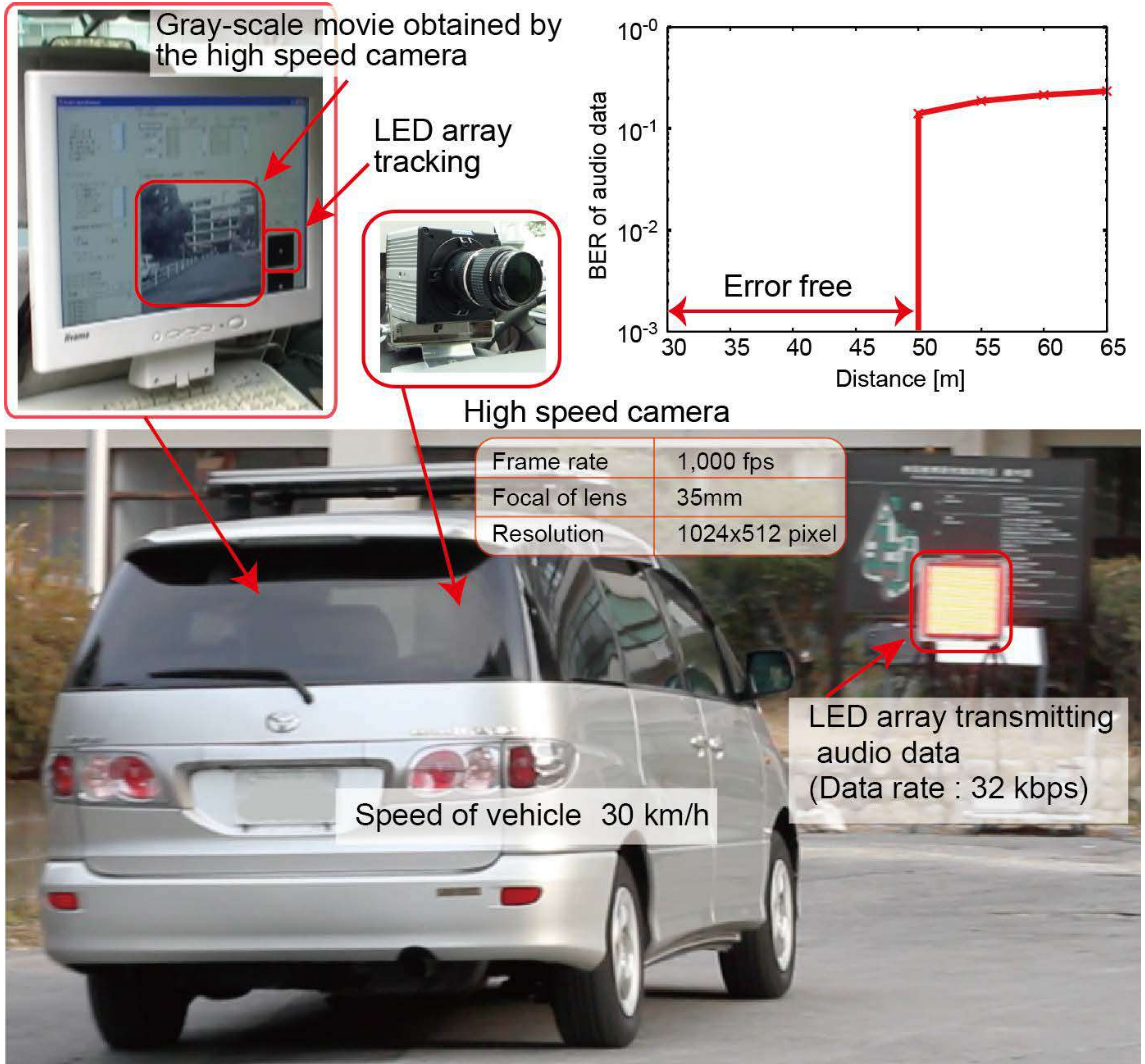


T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.

Fast recognition of LED arrays







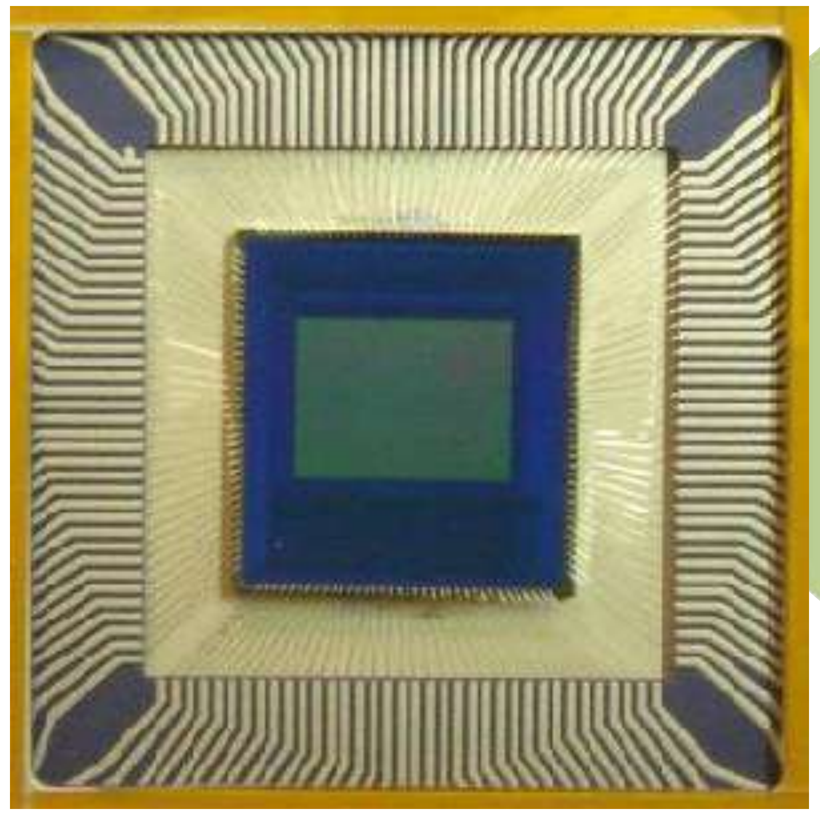
T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.


く76-82

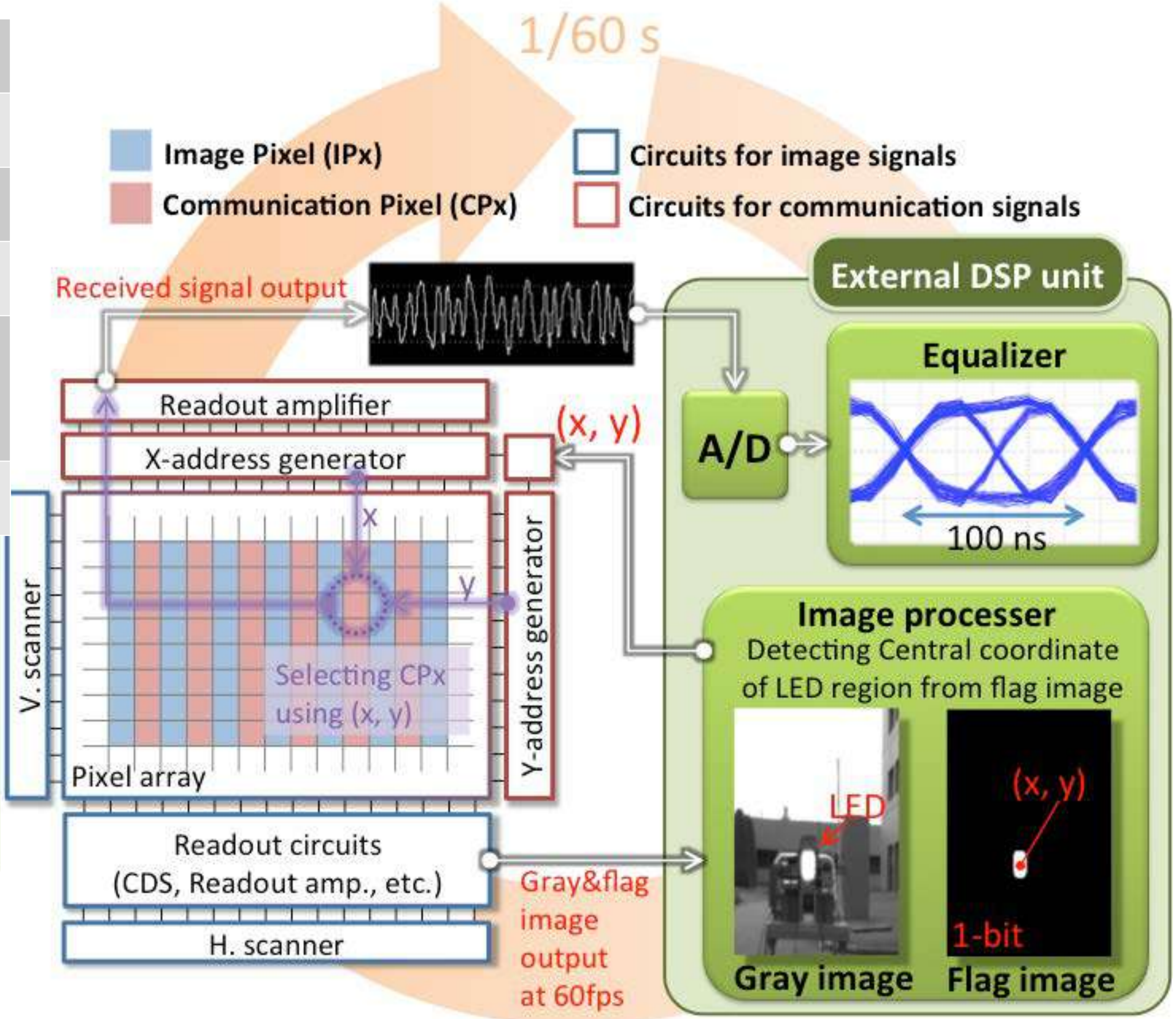
An optical communication image sensor (OCI)

Chip specifications

Technology	*0.18 μm 1P4M CMOS process*
Chip size	*7.5 mm x 8.0 mm*
Imaging area size	*1/3 inch*
Pixel size	*7.5 μm x 7.5 μm*
Number of pixels	*Total of 640 x 480 (VGA)* *- CPx: 320 x 480* *- IPx: 320 x 480*
Frame rate	*Gray and Flag image: 60 fps*



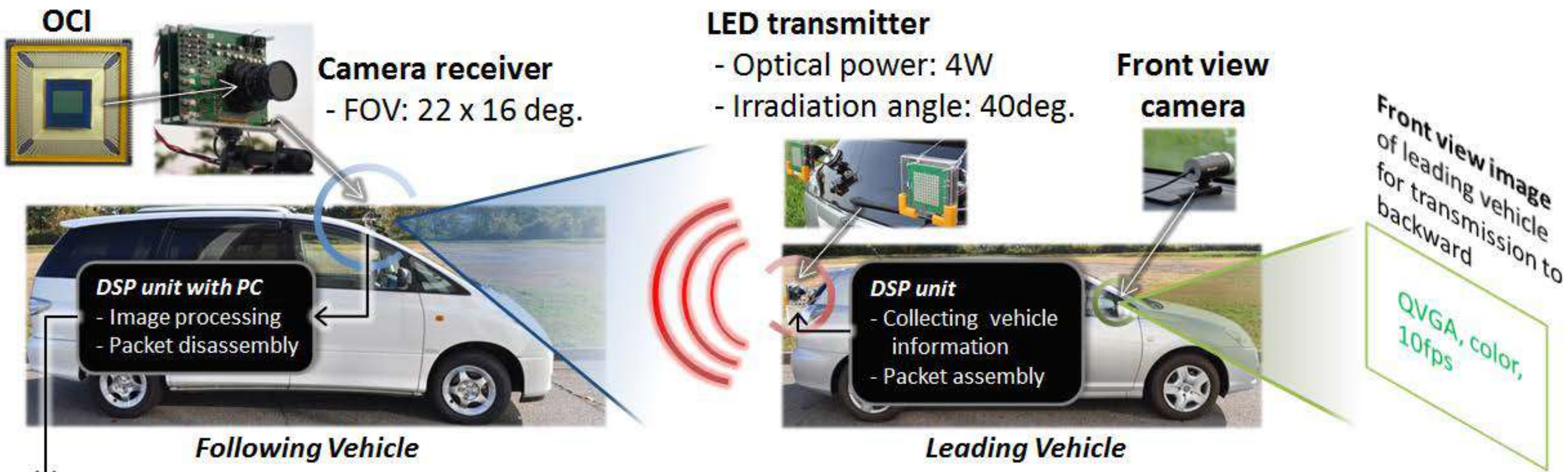
OCI chip photograph

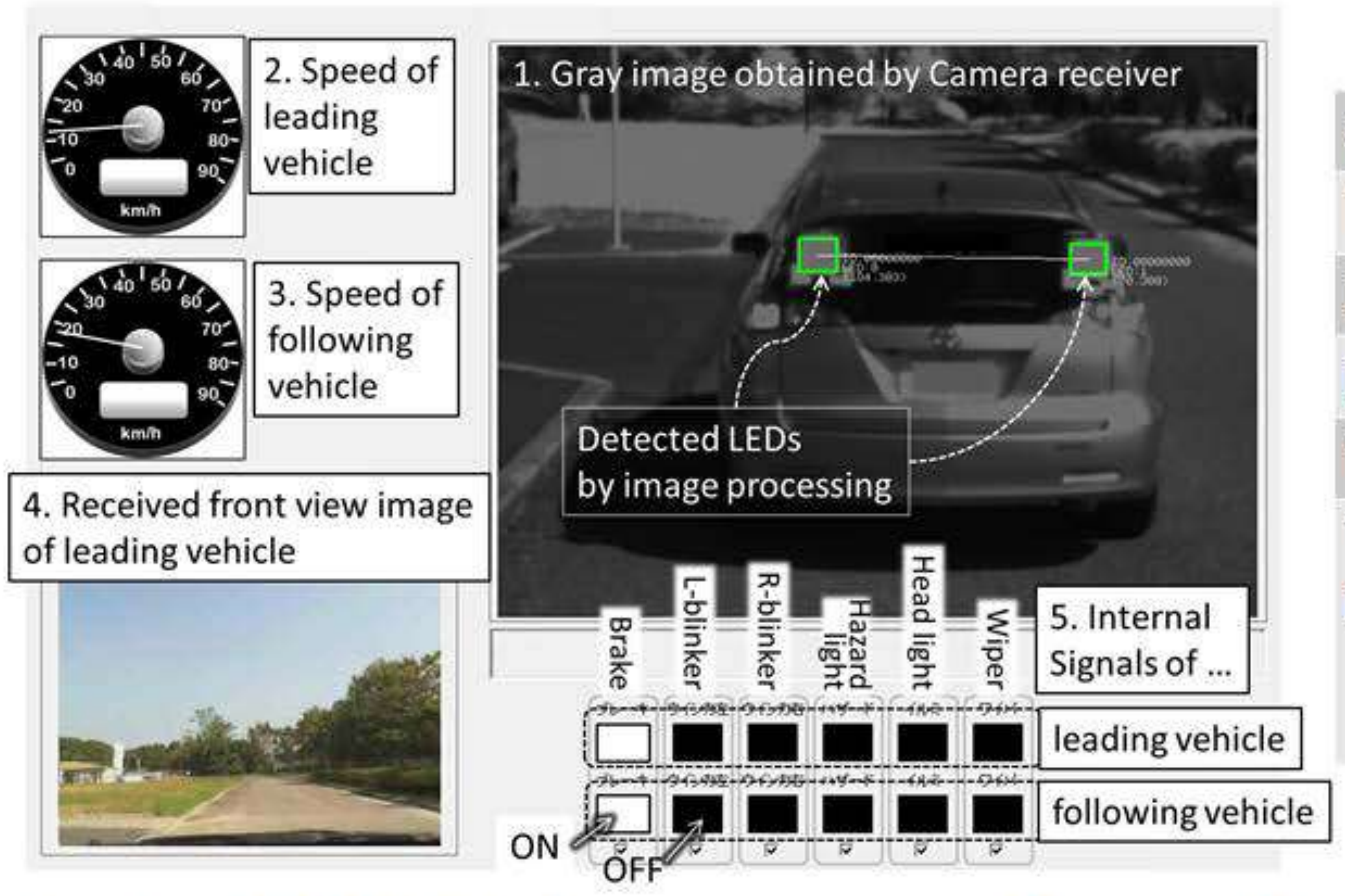


T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.

I. Takai, et al. "LED and CMOS image sensor based optical wireless communication system for automotive applications," IEEE Photonics Journal, Oct. 2013.

Field trial of V2V communication system



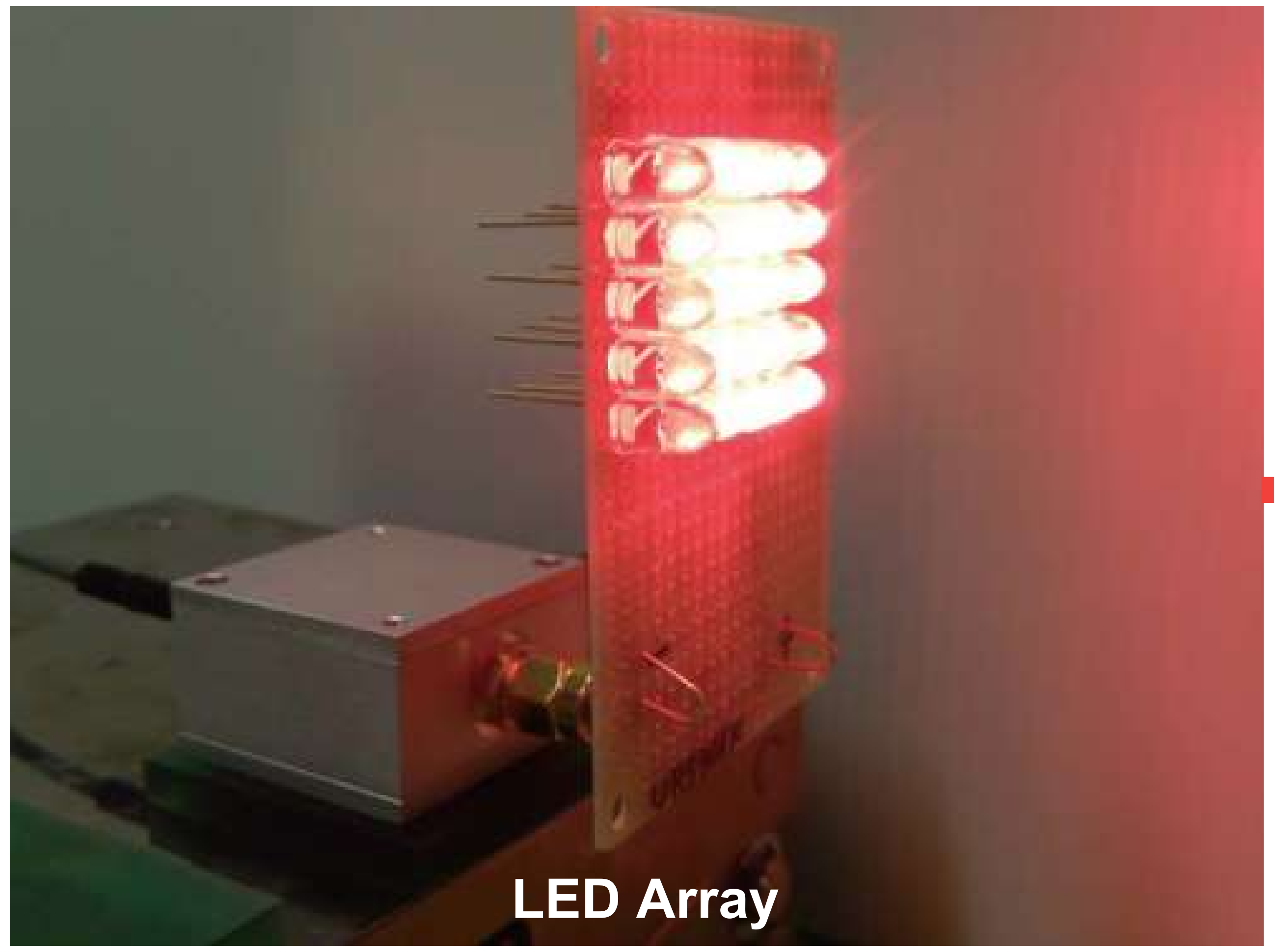


Results of field trial (a image captured a PC monitor)

System specifications

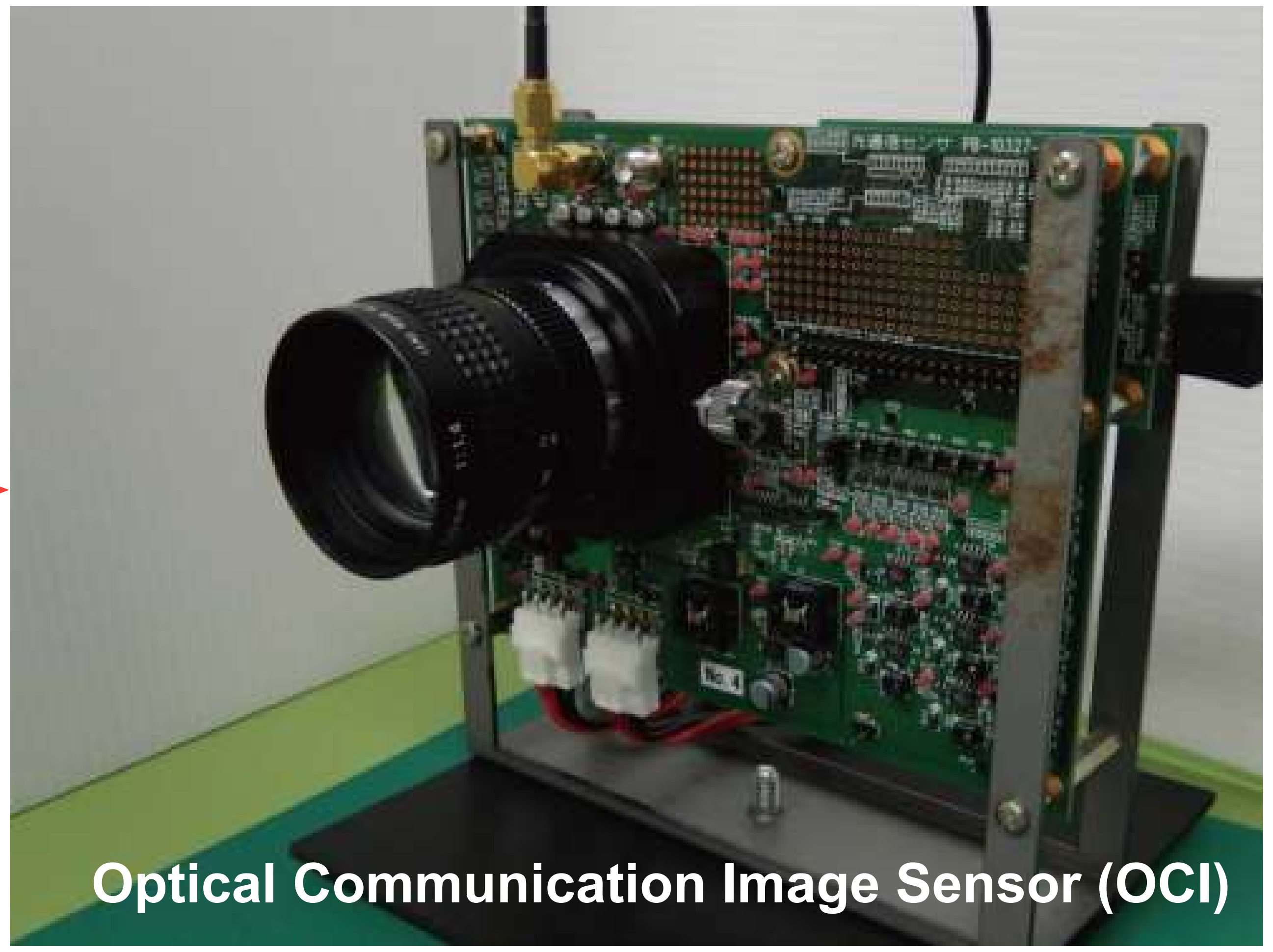
# of LED transmitter	2 units on leading vehicle
Transmission direction	1 way
Encoding method	Manchester code with BCH code
Packet size (payload)	2464 (2392) bit
Transmission rate	10 Mbit/s
Transmission information	Vehicle internal information - ID, car type, car name, speed, - condition of brake, blinker and so on Front view images (QVGA, color, 10fps)

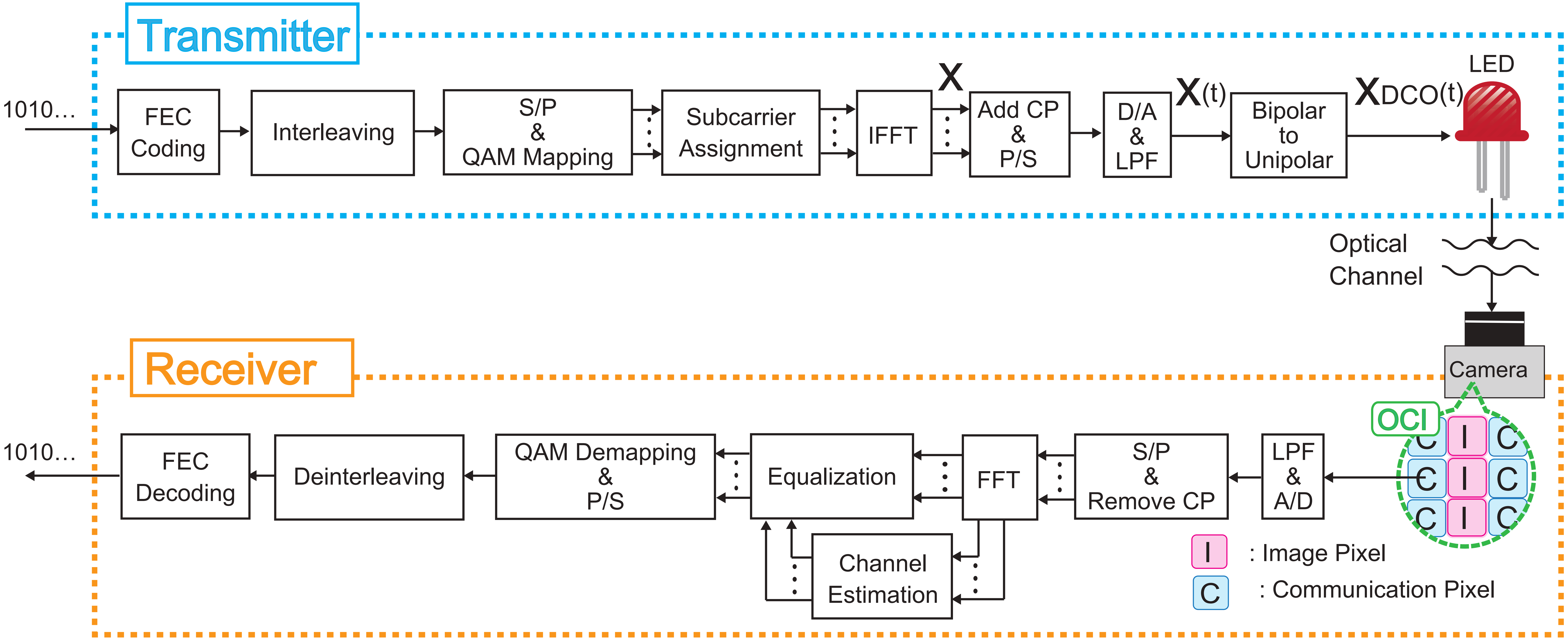
T. Yamazato, et al. "Image Sensor Based Visible Light Communication for Automotive Applications," IEEE Communication Magazine, Jul., 2014.
I. Takai, et al. “LED and CMOS image sensor based optical wireless communication system for automotive applications,” IEEE Photonics Journal, Oct. 2013.



OCI-based Optical-OFDM

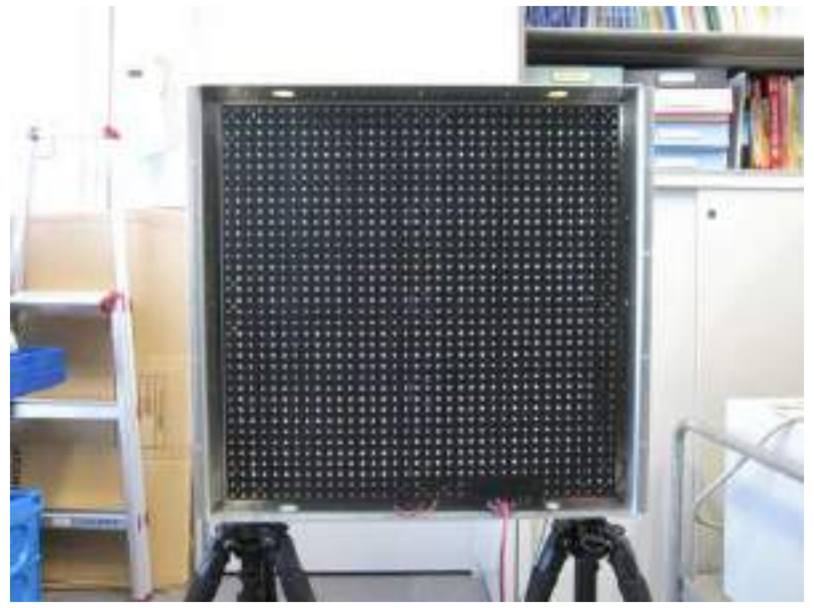
- New automotive VLC system
- 55 Mbps VLC signal transmission
- Faster than DSRC

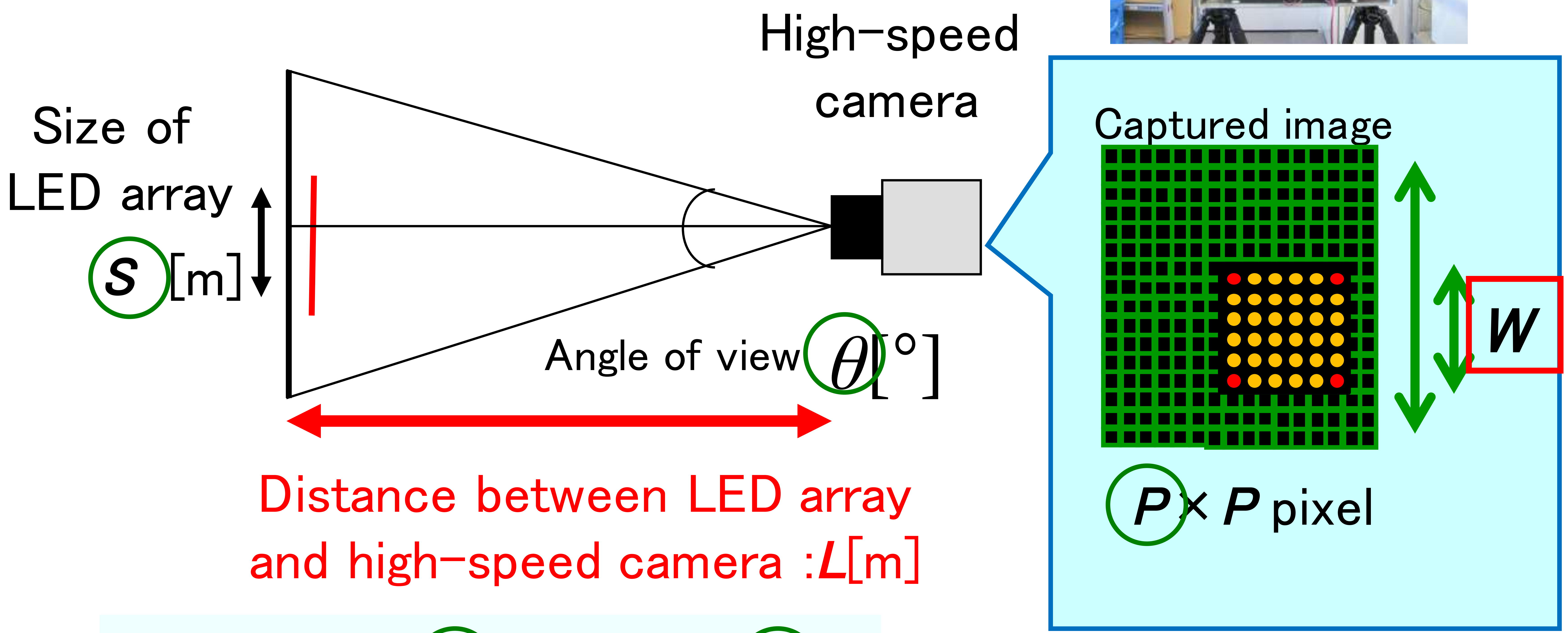




Y. Goto et al. "A New Automotive VLC System Using Optical Communication Image Sensor," IEEE Photonics Journal, Vol. 8, No. 3, June 2016.

How we estimate distance using only one camera

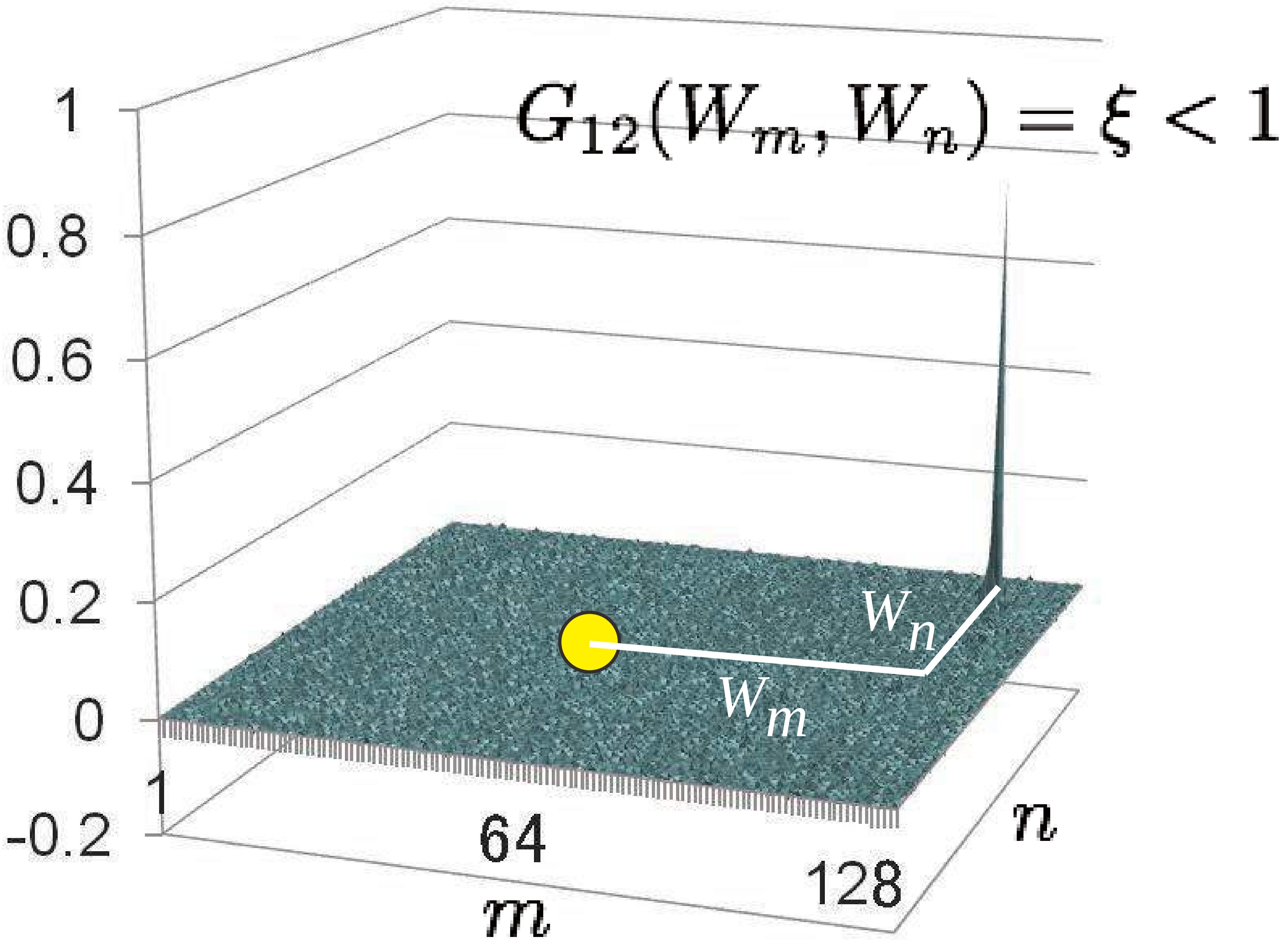




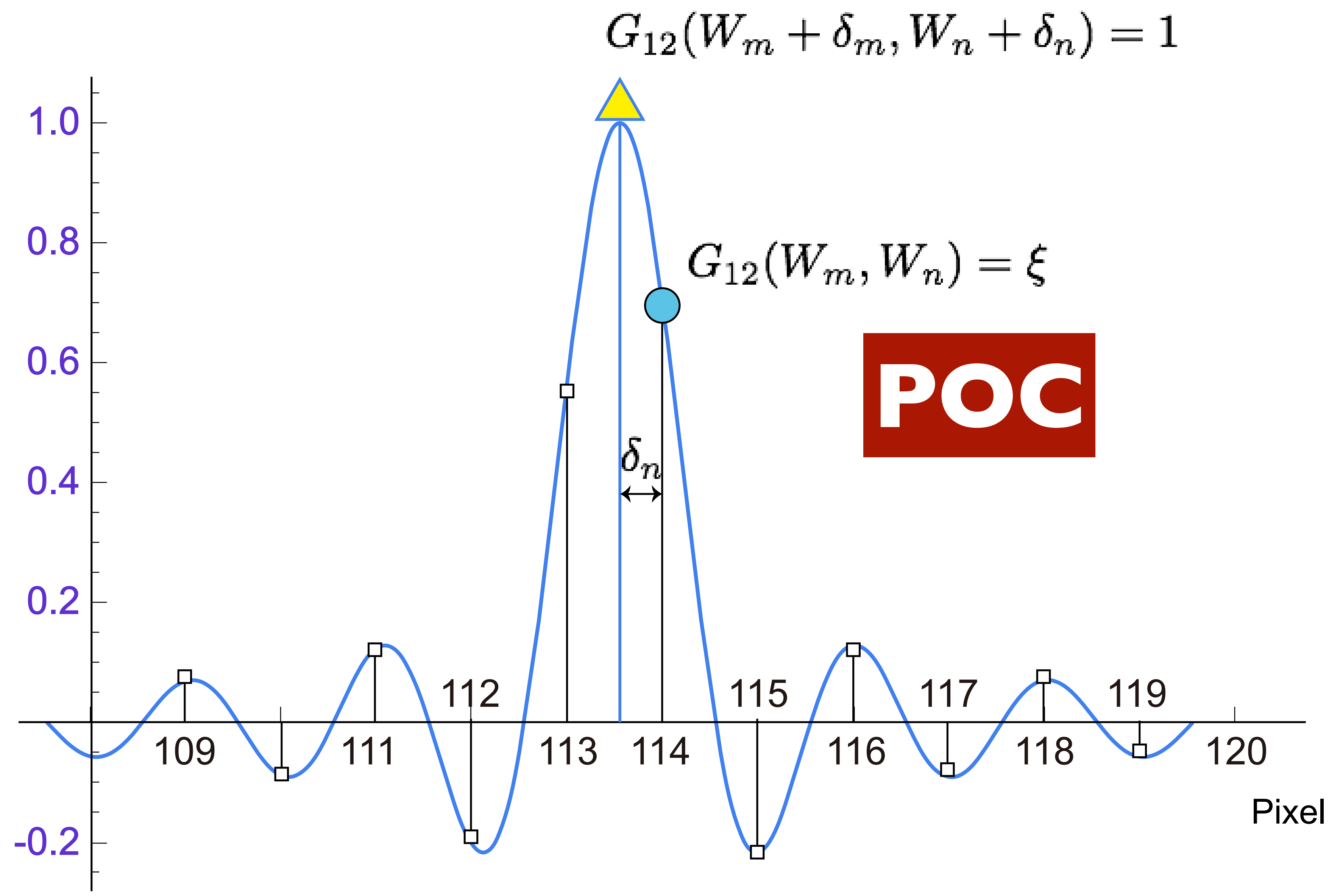
$$\boxed{L} = \frac{1}{2} S \frac{P}{\boxed{W}} \tan^{-1}\left(\frac{\theta}{2}\right)$$

We can estimate distance by using parameter *W*

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



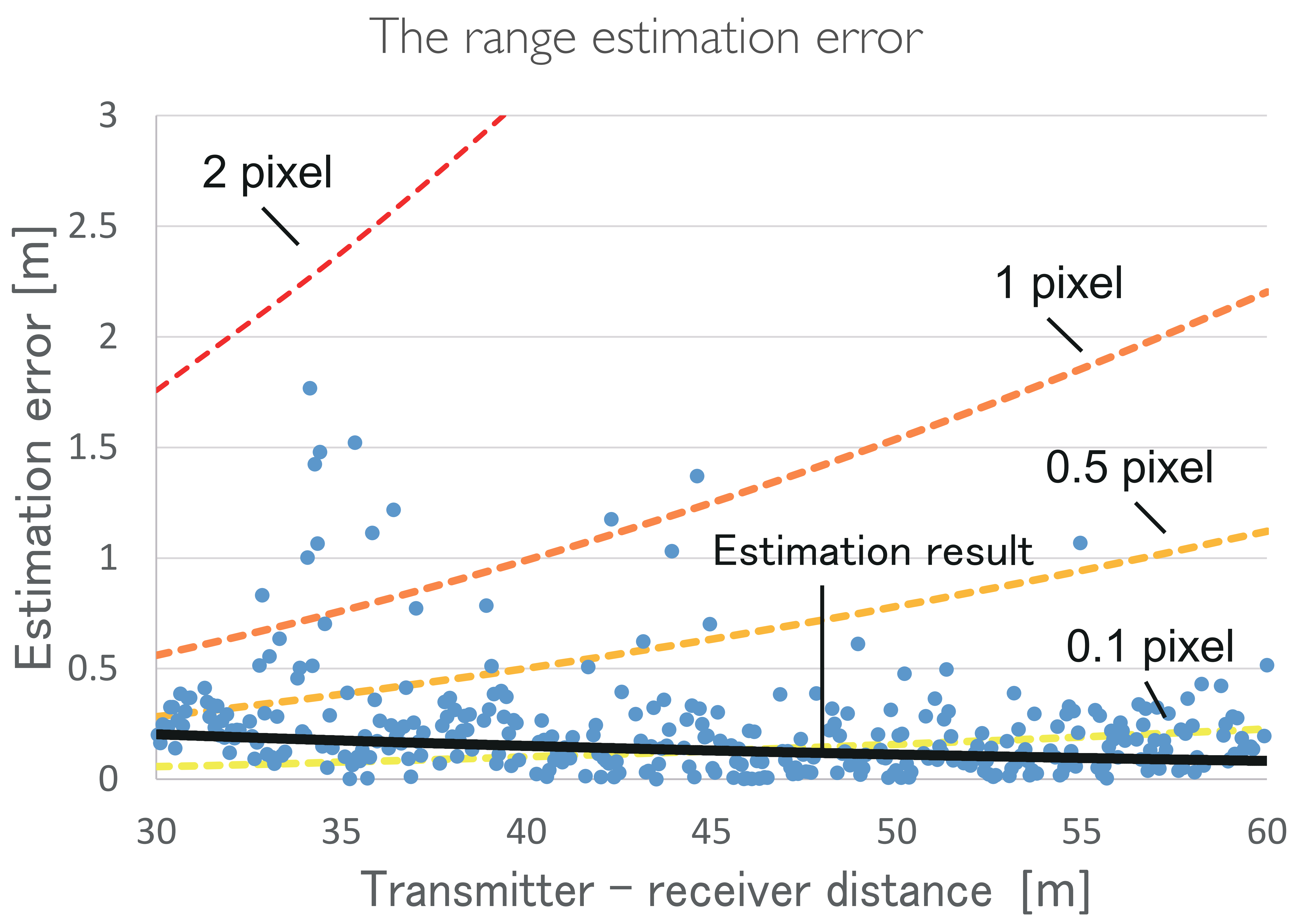
Sinc-approximation



POC

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

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).

Conclusions

- Brief history of LED and invention of blue LED
- Visible light communications (VLC)
  - Camera: spatial separation of sources
- 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
  - Optical communication image sensor (OCI)
    - 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

Thank you and your questions or comments are welcome!

yamazato@nagoya-u.jp

Answer

- Q1
  - What is the name of the material used to manufacture blue LED?
  - Galium nitride (GaN)
- Q2
  - If the source data rate is 120Hz, what is the minimum sampling rate to reconstruct original data?
  - 240 Hz (iPhone slo-mo)