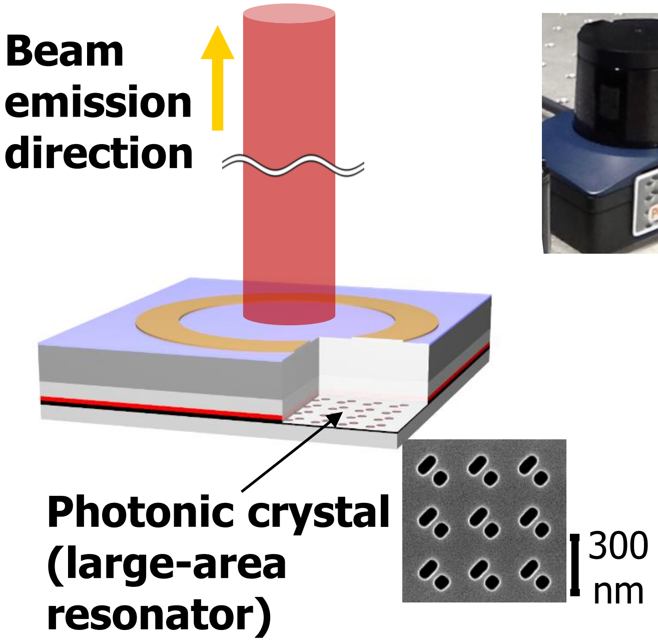
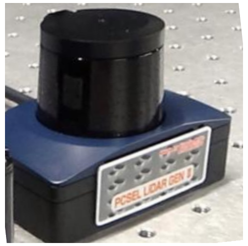
March 2024

「Cross-ministerial Strategic Innovation Promotion Program (SIP) Phase 3 / Construction of smart mobility platform / Development of infrastructure and onboard sensor systems that utilize compact LiDAR technology to understand the actual situations of streets in living areas and busy districts」





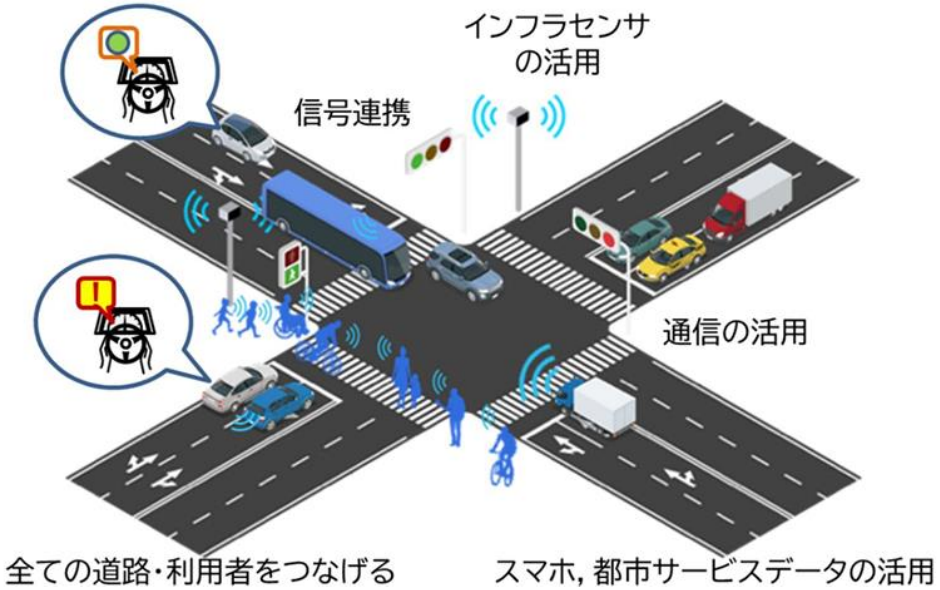
Commissionees: Kanazawa University, Kyoto University 金沢大学 京都大学 KYOTO UNIVERSITY

Table of Contents

Research Background

- Sensing of infrastructure
  - Monitoring the flow of people and traffic, sensing approaching cars, etc.
  - Cooperate with autonomous driving systems
    - RoAD to the L4 Project, etc.
- Importance of LiDAR*-based sensing
  - Application to infrastructure sensors
    - Effective from perspectives of privacy and resolution
  - Application to on-board sensors
    - Application to driver-assistance and autonomous driving systems
- Current state of LiDAR
  - Mostly foreign-made and large-size
    - Domestic production is desirable from the perspective of economic security
  - Reducing the size and cost are expected to have a ripple effect on the automotive industry

https://www.road-to-the-l4.go.jp/activity/theme04/



https://www.road-to-the-l4.go.jp/activity/theme04/pdf/theme04_01.pdf

Taken from the home page of the RoAD to the L4 Project

*Light Detection and Ranging

Research Background

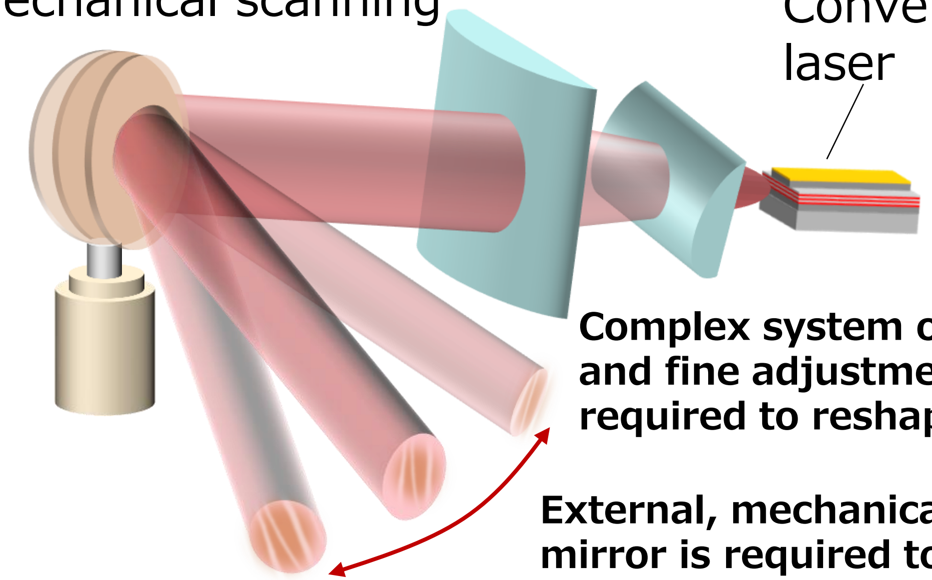
Comparison of conventional semiconductor laser and PCSEL* for LiDAR

Conventional laser

Low brightness: Poor beam quality, wide divergence angle
Poor functionality: No native beam scanning

Mechanical scanning

Conventional laser



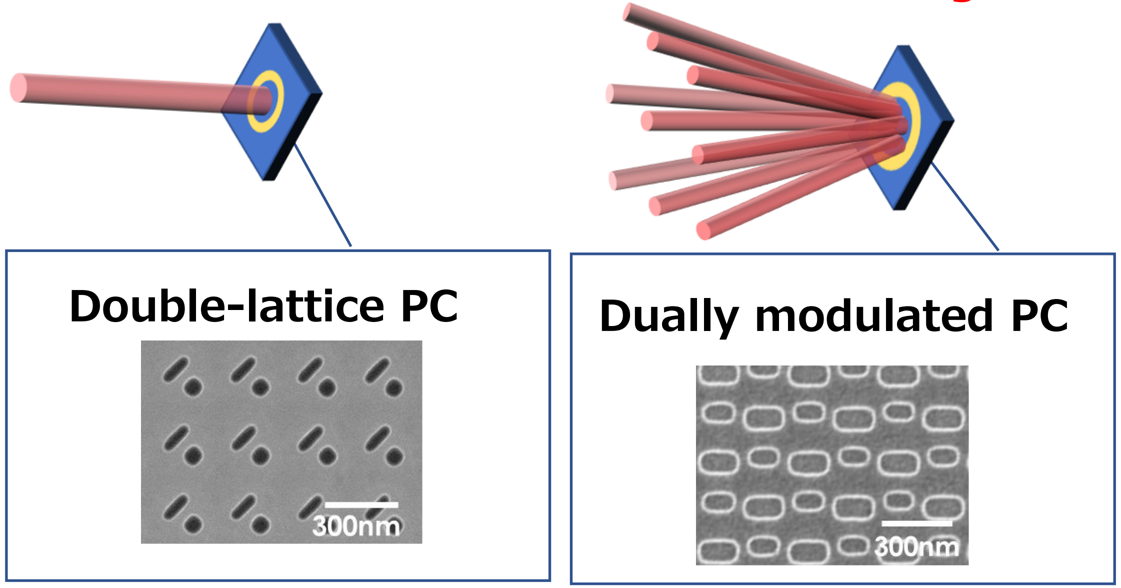
Complex system of lenses and fine adjustments are required to reshape the beam

External, mechanically rotating mirror is required to scan the beam

Bulky, costly LiDAR system: Bottleneck

Photonic crystal laser (PCSEL)

High brightness: High beam quality, narrow divergence angle (lens-free)
High functionality: Capable of multi-dot emission and native beam scanning

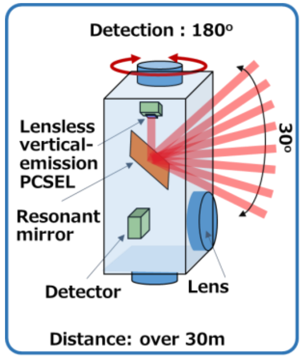


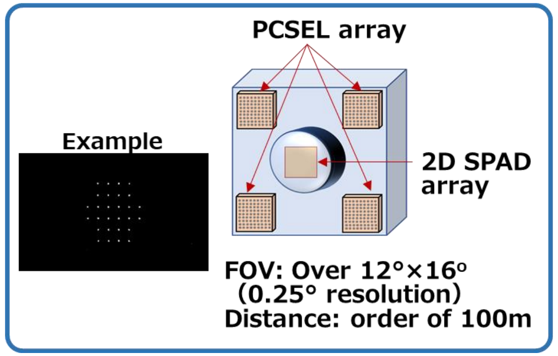
Small, simple, low-cost LiDAR system: Solves the bottleneck

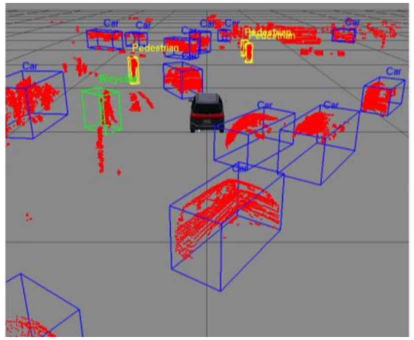
(*PCSEL: Photonic Crystal Surface Emitting Laser)

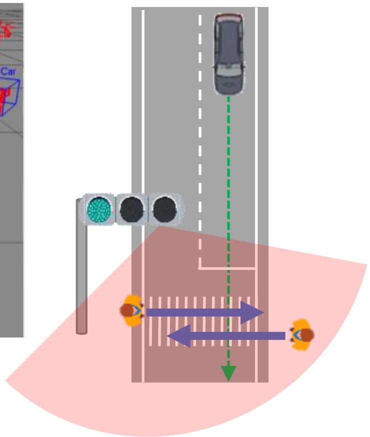
Overview of R&D

- ① **Development of 3D PCSEL-LiDAR system (Kyoto Univ.)**
  - Development of wide-FOV 3D PCSEL-LiDAR (mechanical-type)
    - Use as an infrastructure sensor
    - Use as a sensor for monitoring vehicle blind spots
  - Prototyping & development of non-mechanical PCSEL-LiDAR system
    - Development of low-cost electronically scanned LiDAR
- ② **Development of recognition technology and conducting field-operational test (Kanazawa Univ.)**
  - Development of recognition technology using LiDAR
    - Analysis of point cloud obtained by PCSEL-LiDAR
    - Development of technology for precise detection of vehicles, pedestrians etc.
  - Field-operational test (FOT) using LiDAR
    - Demonstration and verification of use as an infrastructure sensor
      - Expansion to and collaboration with other projects are under consideration
    - Demonstration of autonomous driving using PCSEL-LiDAR
      - Demonstration of L4-equivalent autonomous driving in conjunction with infrastructure sensing









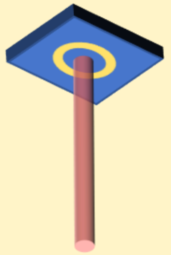
Progress Schedule

Working Items			2023				2024				2025				2026				2027			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
① Develop-ment of 3D PCSEL-LiDAR system	STEP1.「Development of wide-FOV 3D PCSEL-LiDAR」	Improvement and fabrication of vertical-emission-type PCSEL			■	■	■	■														
		Design and prototyping of wide-FOV 3D PCSEL-LiDAR			■	■	■	■	■	■	■	■				■	■	■				
	STEP2.「Development of non-mechanical 3D PCSEL-LiDAR」	Design, fabrication, and deepening of multi-dot emission-type PCSEL			■	■	■	■	■	■	■	■	■	■	■	■	■	■				
		Procurement of SPADs and development of a control unit			■	■	■	■	■	■	■	■	■	■	■	■	■	■				
		Design and development of PCSEL driving circuit			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
		Design and prototyping of nonmechanical 3D PCSEL-LiDAR			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Additional item	Development of card-type LiDAR	Prototyping of card-type wide-FOV 2D PCSEL-LiDAR				■	■	■	■													
② Develop-ment of recognition technology and conducting field-operational test	A.「Development of recognition technology using LiDAR」	Survey of the latest recognition algorithms			■	■																
		Building a virtual sensing environment					■	■	■	■												
		Development of recognition algorithms with small-scale computing devices									■	■	■	■								
		Improvement of recognition models for expanding detection range													■	■	■	■				
		Construction of recognition models cooperated with infrastructure and on-vehicle sensors																	■	■	■	■
	B.「Field-operational test (FOT) using LiDAR」	Evaluation of existing LiDAR sensor			■	■																
		Public road experiment with existing LiDAR sensor			■	■	■	■	■	■	■	■										
		FOT with wide-FOV LiDAR as infrastructure sensor											■	■								
		FOT with wide-FOV LiDAR as on-vehicle sensor											■	■	■	■	■	■				
		Construction of test vehicles equipped with multiple PCSEL-LiDAR, etc.									■	■	■	■	■	■	■	■				
		FOT cooperated with infrastructure sensors and on-vehicle sensors																	■	■	■	■

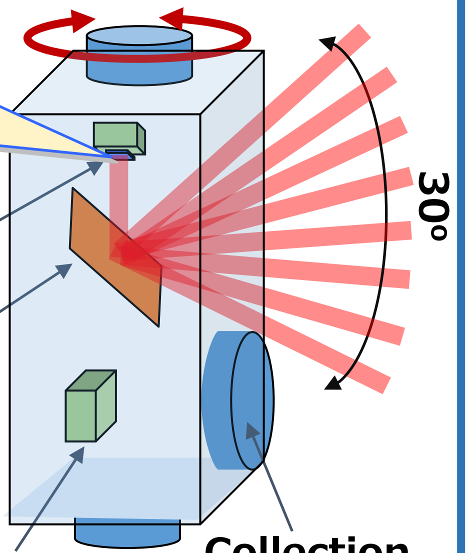
R&D Goals : ① 3D PCSEL-LiDAR System

STEP1: Wide-FOV 3D PCSEL-LiDAR

Vertical-emission-type PCSEL



Wide-range detection : 180°

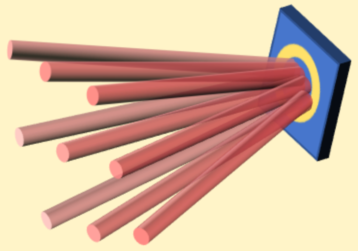


Distance: over 30m

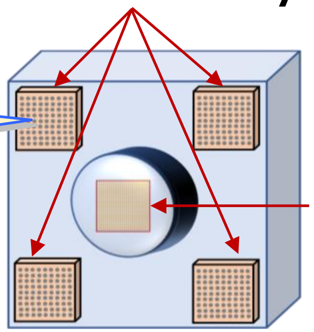
For use as an infrastructure sensor and a sensor that measures distances in a vehicle's blind spots

STEP2: Non-mechanical 3D PCSEL-LiDAR

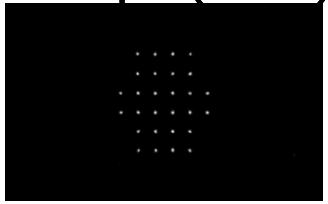
Multi-dot PCSEL



PCSEL array

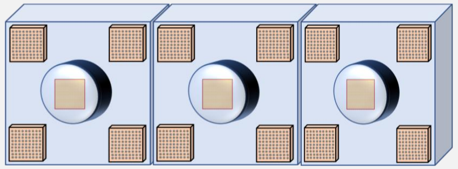


Example (video)



FOV: Over 12°×16°
(0.25° resolution)
Distance: order of 100m

(Note 1) Can widen the FOV by stacking multiple systems



(Note 2) In the future, by improving the performance of SPADs and by increasing the peak power of PCSELs, ranging of 200m to 300m will be possible. Moreover, the number of SPAD pixels and the PCSEL irradiation area (number of points) can be expanded to achieve a wider FOV.

For realizing all-semiconductor chips, which are expected to be smaller and less expensive, and for use as a general sensor for vehicles

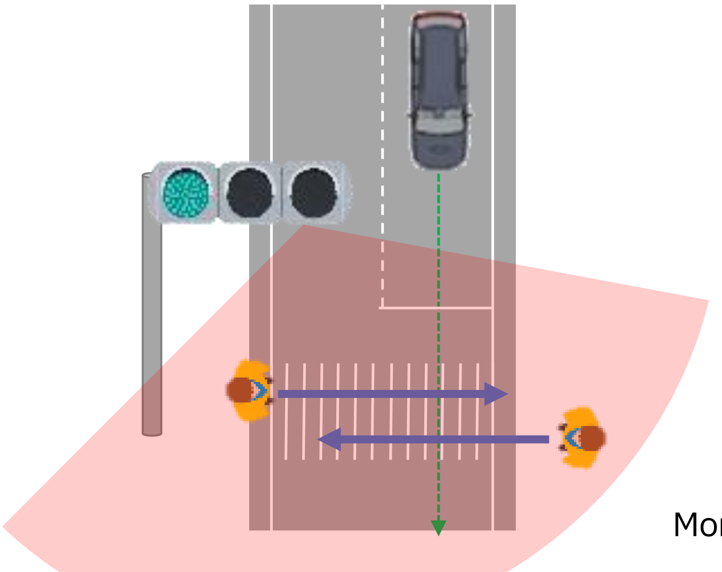
R&D Goal : ② Development of Recognition Technology and Conducting Field-operational Test

Mid-term goal :
Conducting FOT using infrastructure sensing

Development of recognition algorithms using wide-FOV 3D PCSEL-LiDAR, and conducting field operational test

Final goal :
Conducting FOT of level4 equivalent autonomous driving

Development of recognition algorithms using multi PCSEL-LiDAR, and conducting field operational test with cooperating infrastructure and on-board sensors.

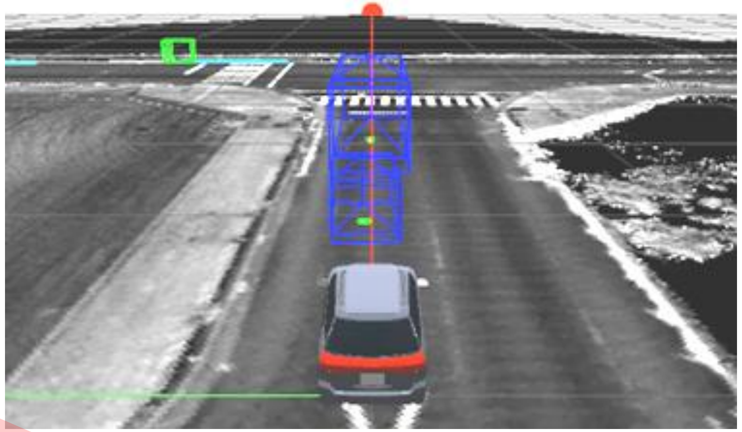


Monitoring crossing pedestrian
(Wide-FOV PCSEL-LiDAR)

Cooperating infrastructure and on-board sensors

Monitoring blind spot near vehicle
(Wide-FOV PCSEL-LiDAR)

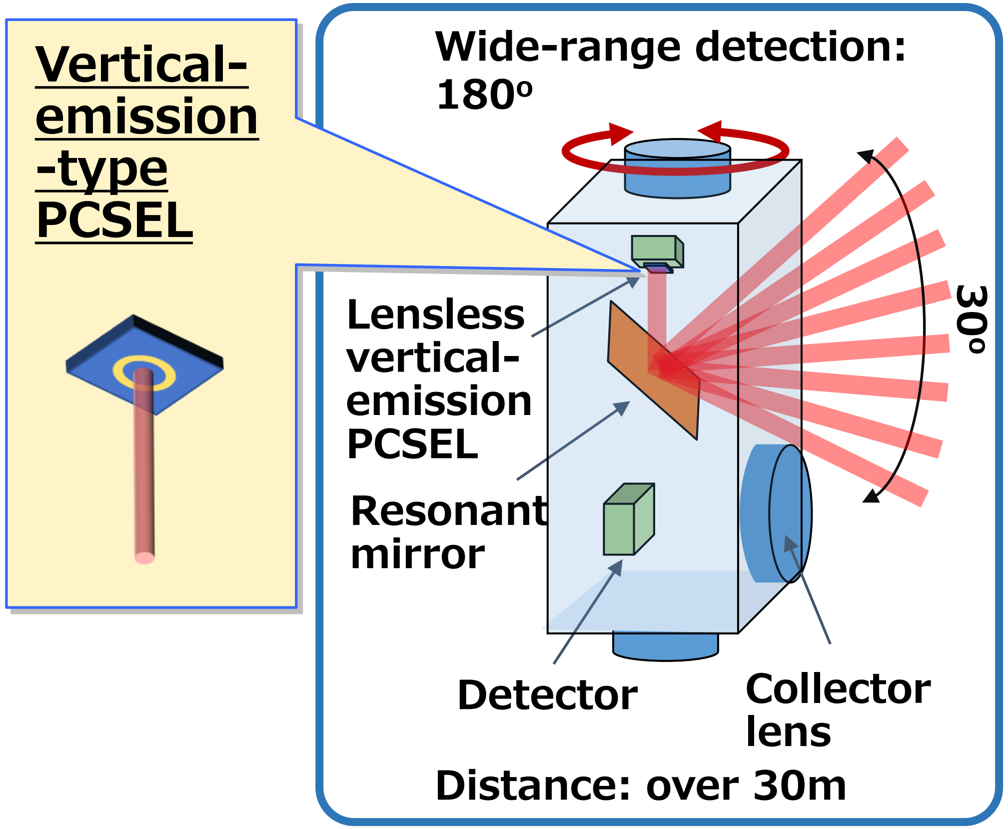
Monitoring in front of vehicle
(Nonmechanical PCSEL-LiDAR)



Recognition using on-board sensors

Result of Current FY: Development of Wide-FOV 3D PCSEL-LiDAR

STEP1 : Wide-FOV 3D PCSEL-LiDAR



For use as an infrastructure sensor and a sensor that measures distances in a vehicle's blind spots

Development items
(red text is progress in the current FY)

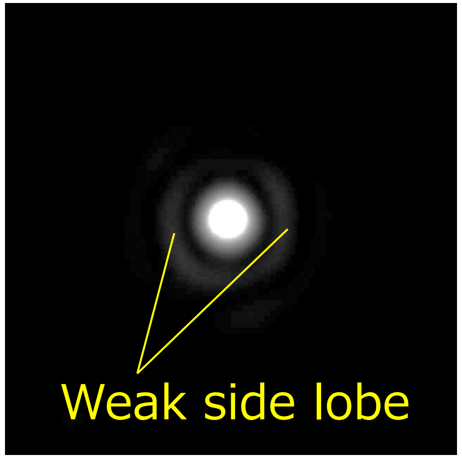
- **Improvements of vertical-emission-type PCSEL (realizing an ideal Gaussian beam) and fabrication**
- **Prototyping of 3D PCSEL-LiDAR**

(Additional item for inter-project collaboration: Prototyping of card-type 2D wide-FOV PCSEL)

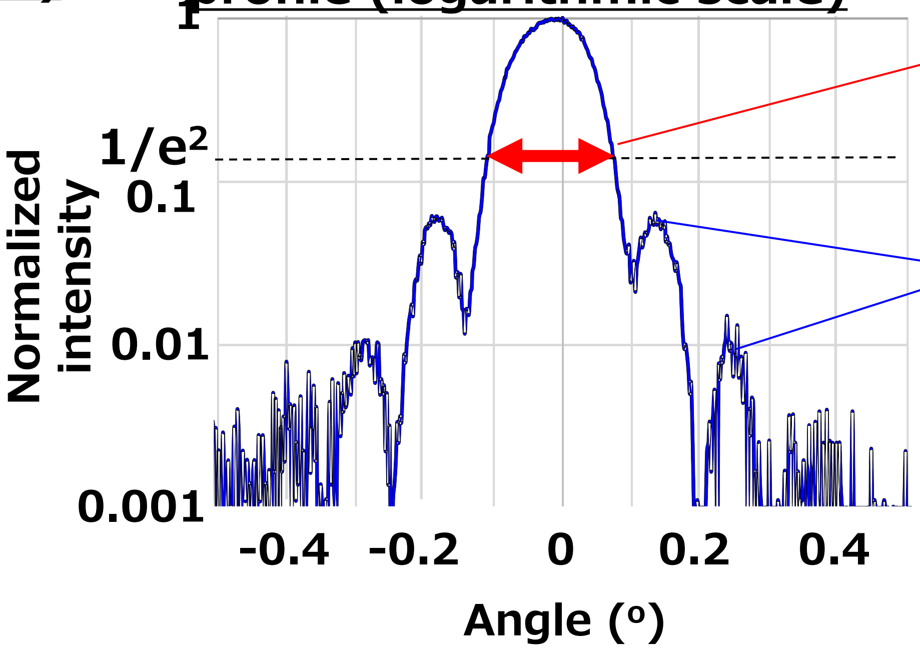
Realizing an Ideal Gaussian Beam with a Vertical-emission-type PCSEL

Device used in 2D PCSEL-LiDAR up until now

Emitted beam pattern (brightness enhanced)



Cross-sectional intensity profile (logarithmic scale)



Narrow divergence angle (<0.2°) already achieved

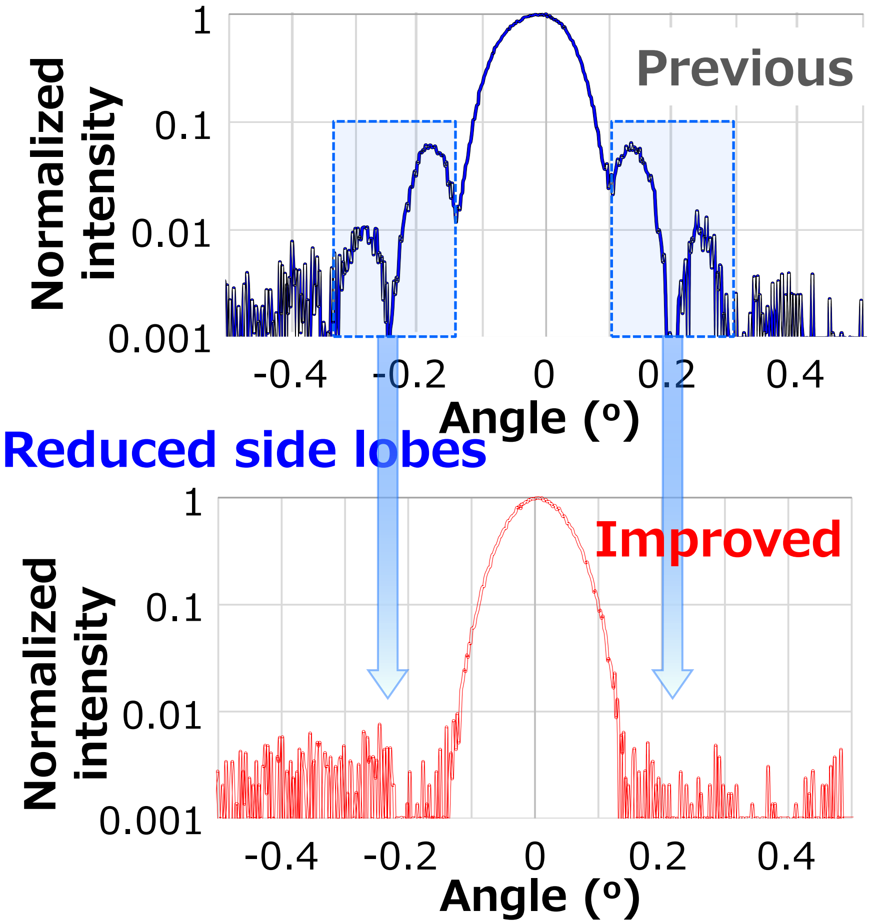
Presence of outlying side lobes, whose intensity is around 1/30 of that of the main lobe

May cause erroneous detection of obstacles in directions other than the one to be measured, and must be suppressed

Goal: Reduce intensity to under 1/1000 that of the main lobe

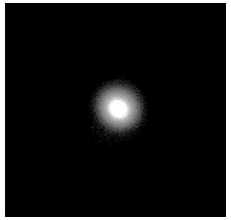
Measured Lasing Characteristics of Fabricated PCSEL

Intensity profile of the emitted beam

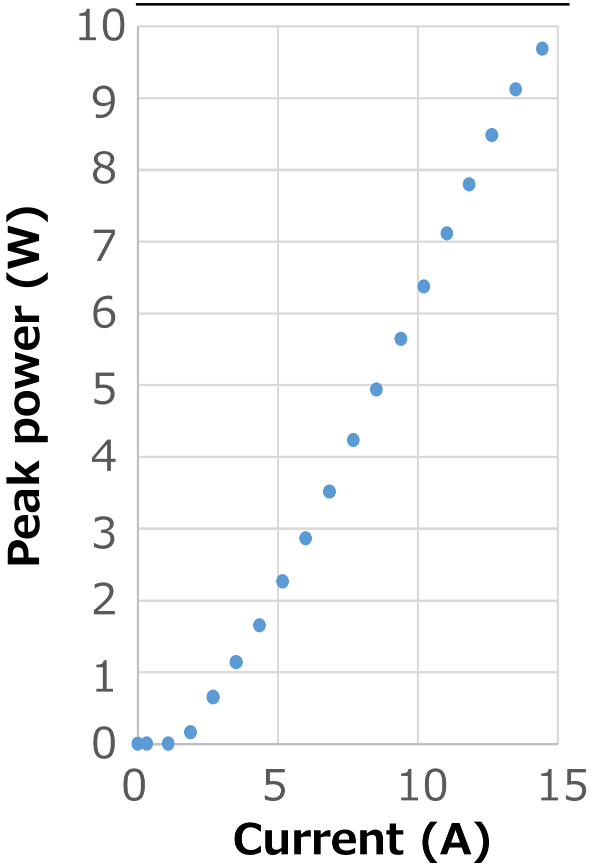


Beam pattern (brightness enhanced)

Beam pattern (brightness enhanced)



I-L characteristic



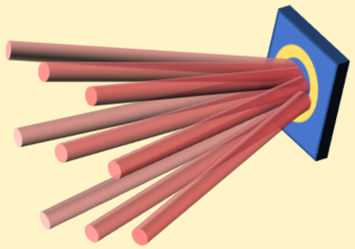
Successfully realized side-lobe reduction + high-power operation

Next step: Provide to Hokuyo Automatic (recommissioning company) for development of wide-FOV 3D PCSEL-LiDAR

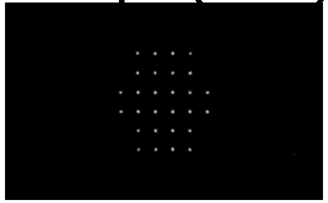
Result of Current FY: Development of Non-mechanical 3D PCSEL-LiDAR

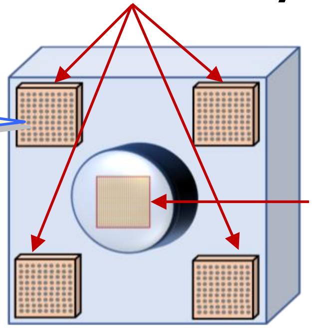
STEP2: Non-mechanical 3D PCSEL-LiDAR

Multi-dot PCSEL



Example (video)





FOV: Over 12°×16°
(0.25° resolution)
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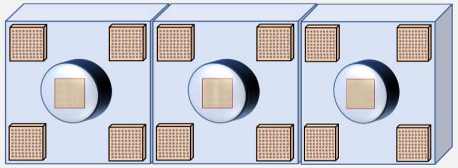
(Note 1) Can widen the FOV by stacking multiple systems



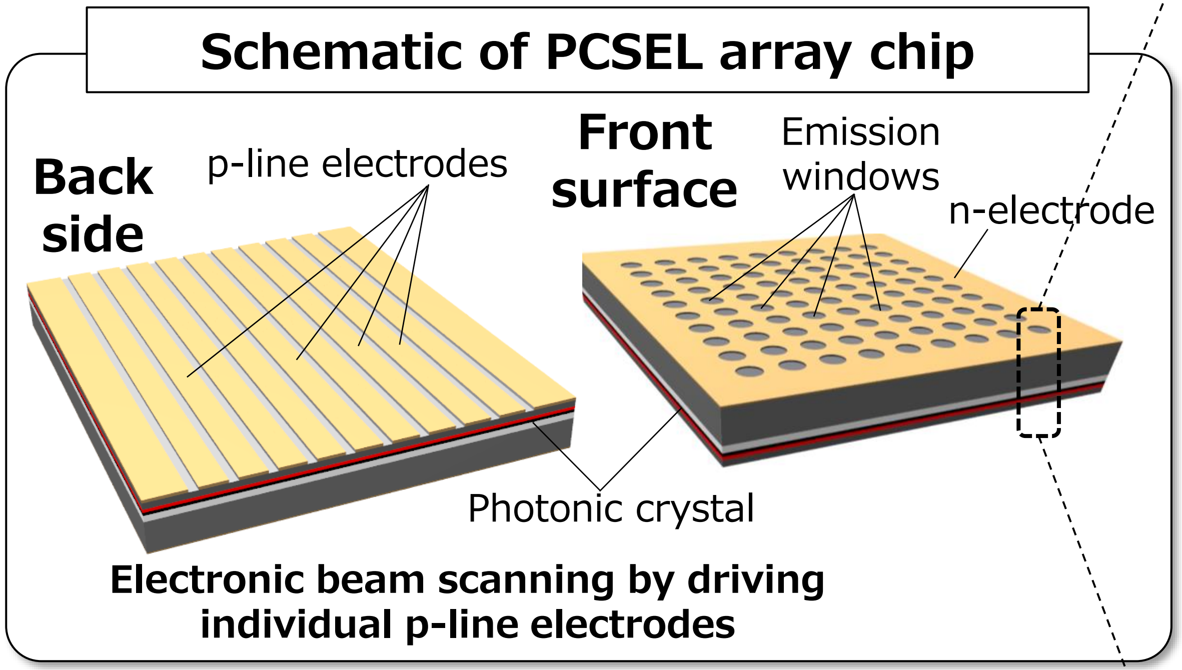
(Note 2) In the future, by improving the performance of SPADs and by increasing the peak power of PCSELs, ranging of 200m to 300m will be possible. Moreover, the number of SPAD pixels and the PCSEL irradiation area (number of points) can be expanded to achieve a wider FOV.

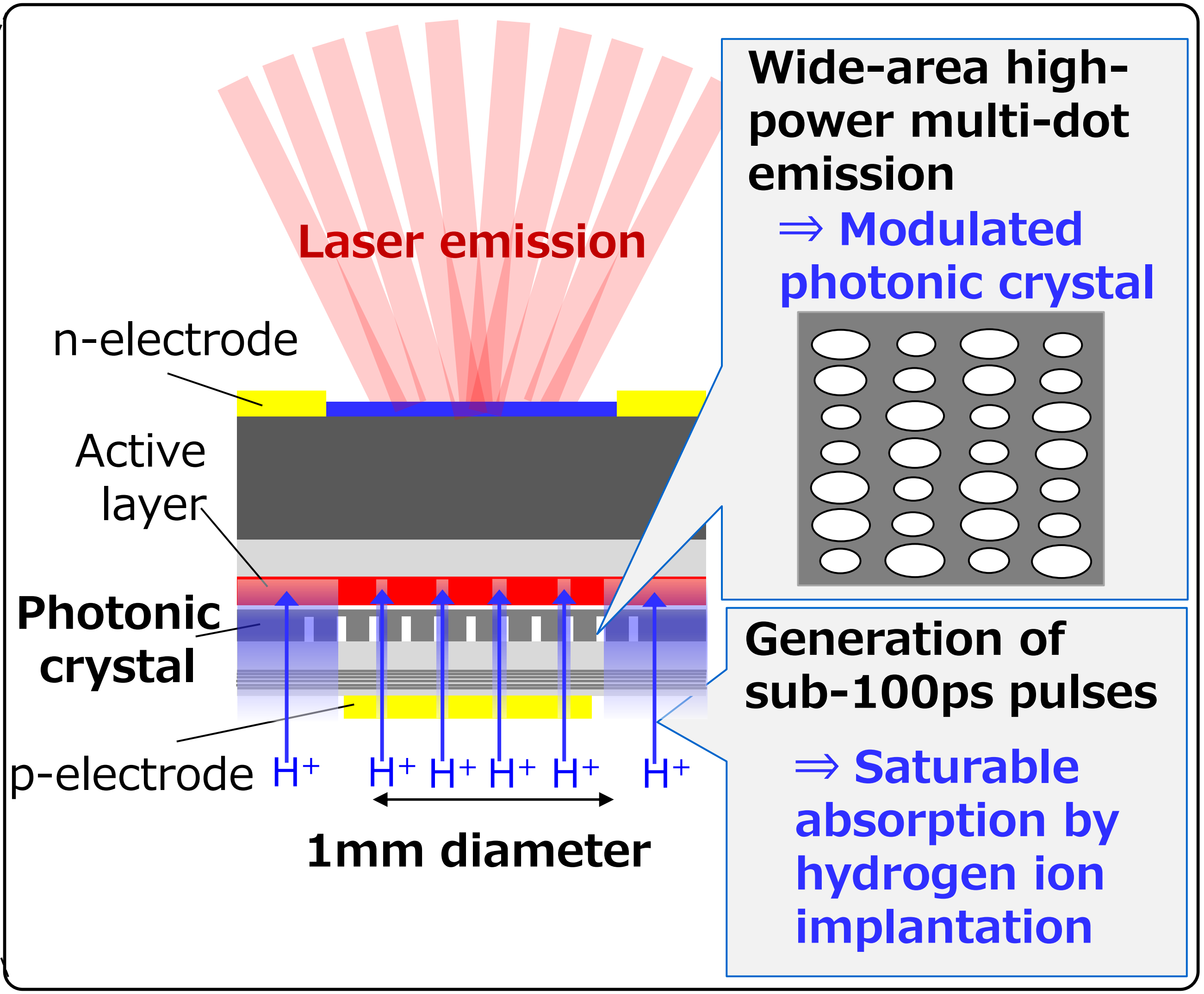
For realizing all-semiconductor chips, which are expected to be smaller and less expensive, and for use as a general sensor for vehicles

Development items (red text is progress in the current FY)

- **Design and fabrication of multi-dot-emission, ultra-short-pulse PCSEL**
- **Procurement and evaluation of 2D SPAD array**
- Fabrication of PCSEL driving circuit and design and prototyping of nonmechanical 3D PCSEL-LiDAR
- Theoretical verification of 200m-300m ranging

Multi-dot-emission, Ultra-short-pulse PCSEL





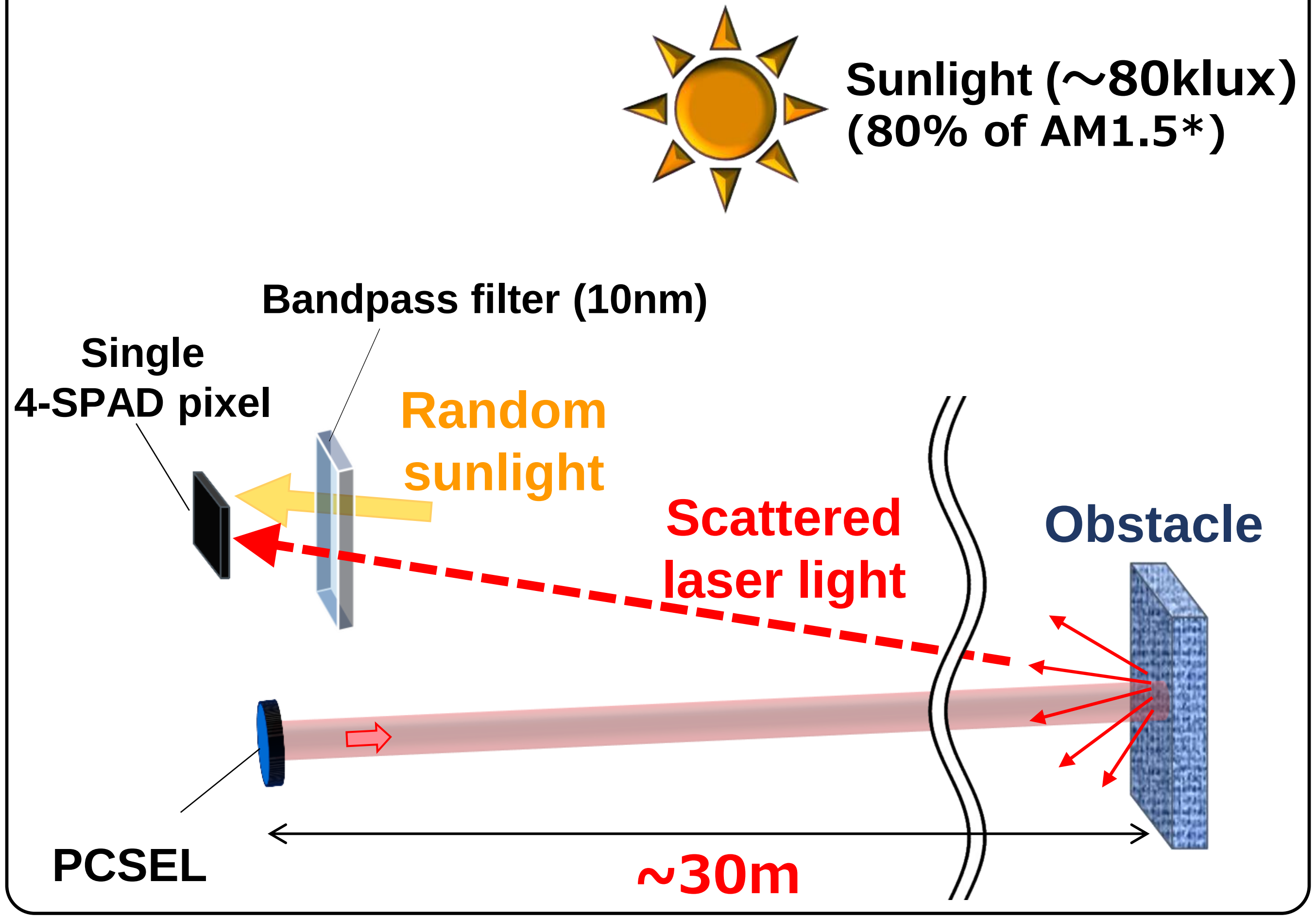
Completed basic design of modulated PCSEL with saturable absorption

Procurement and Basic Evaluation of 2D SPAD

Specifications

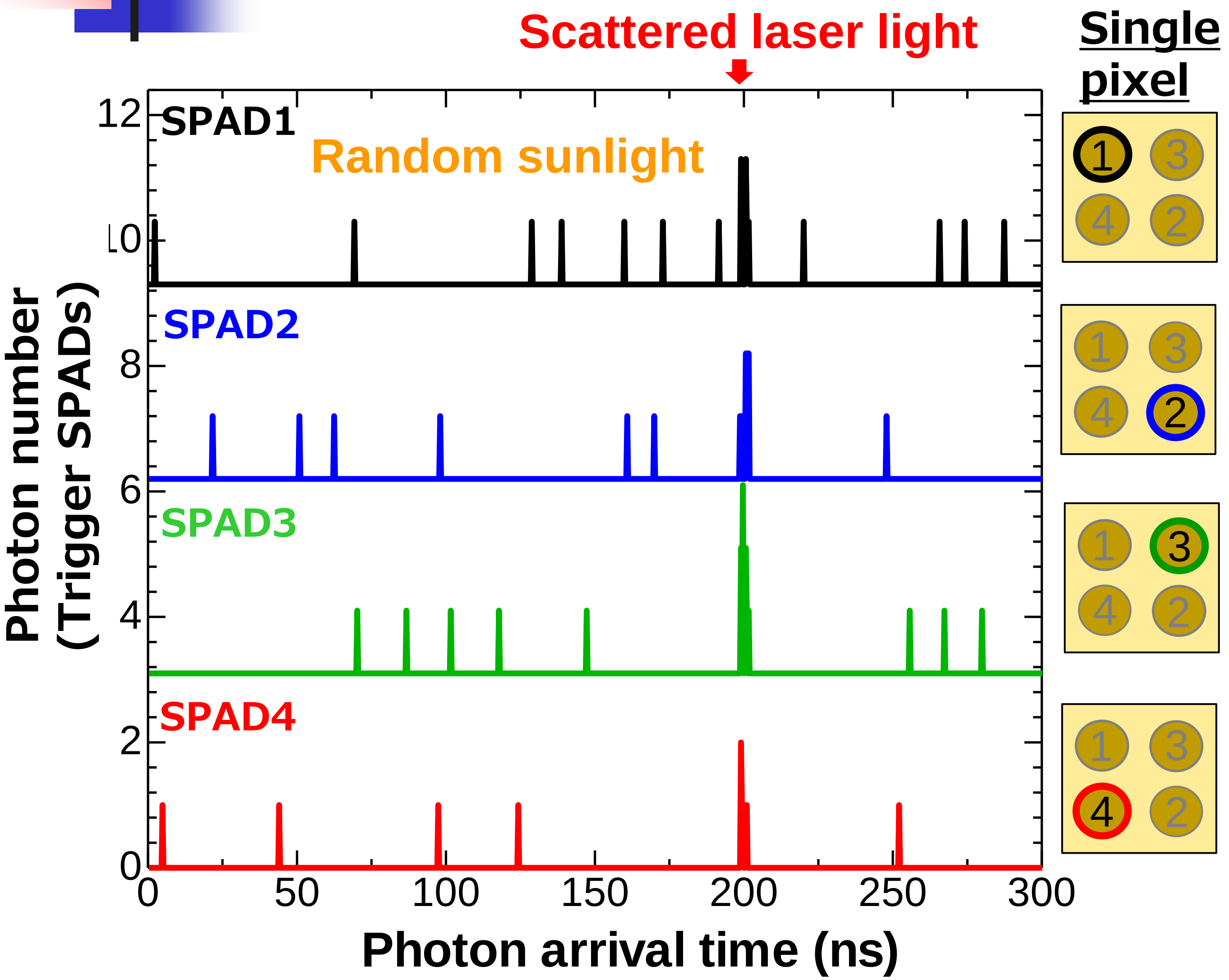
Item	Value
Pixels	64×48 (3,072 in total)
SPADs per pixel	4 (2×2)
Pixel size	130μm×130μm
Array size	8.4mm×6.5mm

Schematic of basic distance measurement by SPADs

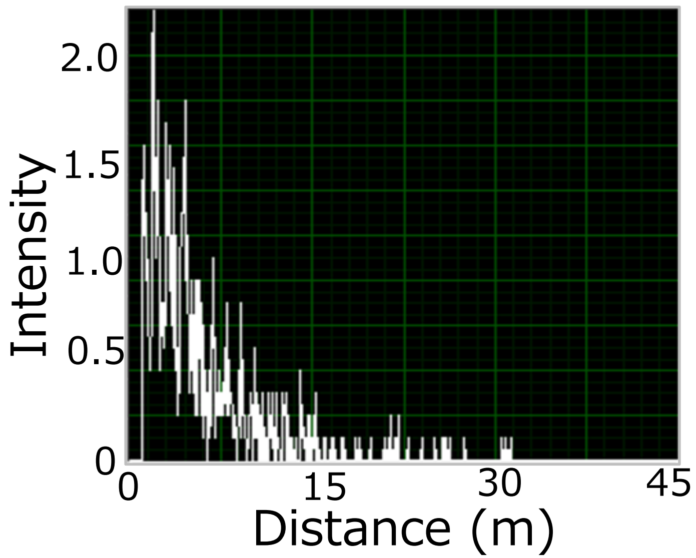


*AM1.5 : World-standard Air Mass 1.5 solar intensity ($1kW/m^2$), illuminance ~100klux

Basic Evaluation of SPADs

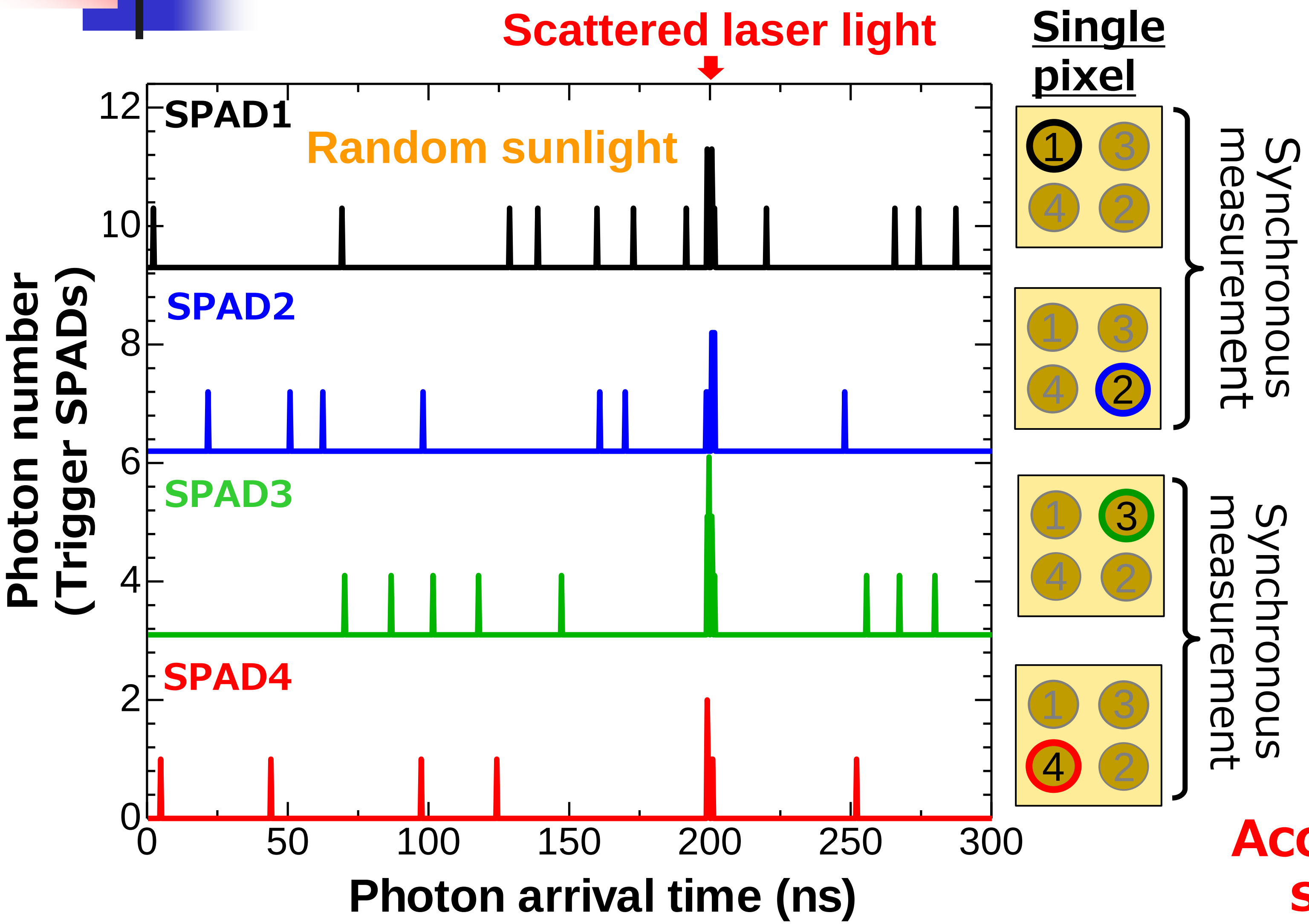


Asynchronous measurement

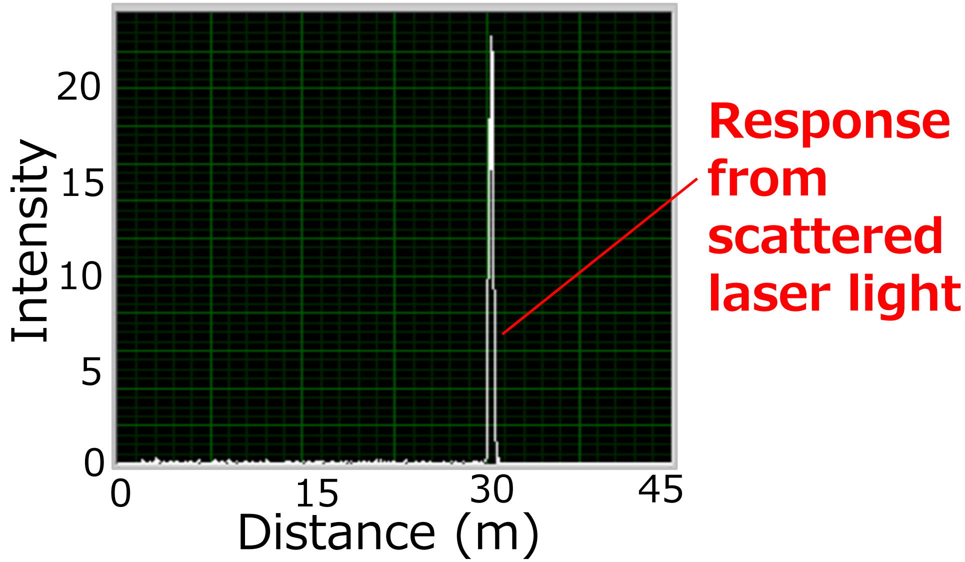


Number of integrations: around 200

Basic Evaluation of SPADs



Synchronous measurement (1,2)∨(3,4)



Number of integrations: around 200

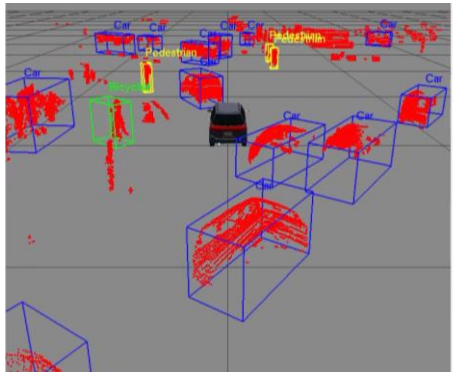
Accurate ranging is possible via synchronous measurement

Next step: Detailed evaluation and design and fabrication of LiDAR system

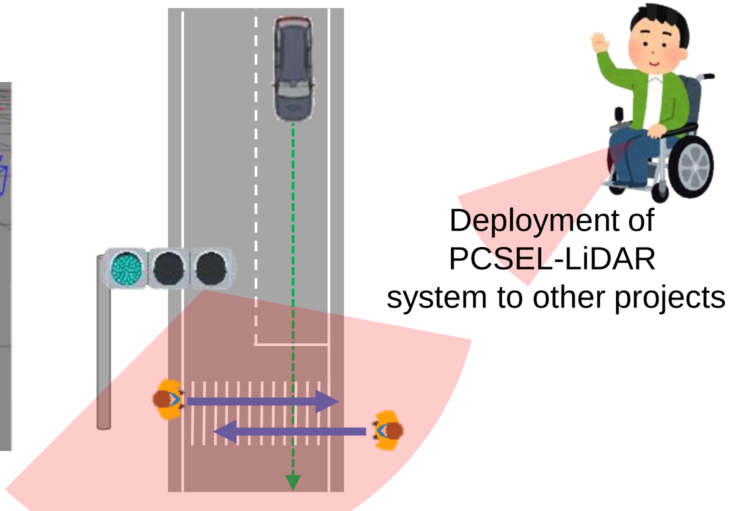
Development of Recognition Technology and Field-operational Test

- Achievement of SIP Phase 2 (SIP-adus)*
  - Autonomous driving system
    - R&D of recognition technology using on-board sensors
  - Field-operational test using infrastructure
    - FOTs at Tokyo waterfront area
- R&D contents in this project
  - Development of recognition technology using LiDAR
    - Applying LiDAR to infrastructure sensor
      - Monitoring crossing pedestrians, etc.
    - Utilizing LiDAR as onboard sensor
      - Development of recognition technology and sensor evaluation
  - Field-operational test (FOT) using LiDAR
    - Deployment of PCSEL-LiDAR system to other projects
    - Testing of level 4-equivalent autonomous driving with cooperating infrastructure sensors

*SIP Phase 2 (SIP-adus)



Development of recognition technology using LiDAR



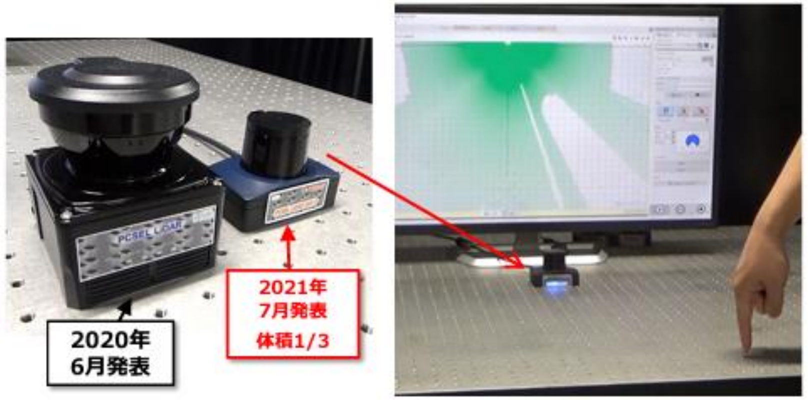
Cooperate with infrastructure sensor and onboard sensor

Overview of R&D in FY2023

- Survey of LiDAR recognition algorithms
  - Basic study of recognition technology to be developed
    - Basic implementation of object detection DNN * model
- Evaluation test of existing LiDAR sensor
  - Evaluation under diverse weather conditions
    - Testing at Japan Automobile Research Institute (JARI) under backlighting, rain, and fog conditions
  - Recognition distance evaluation of existing 3D LiDAR sensors
    - Understanding the characteristics of existing LiDAR
      - Evaluation focus on VLS-128AP made by Velodyne (Ouster)
      - Latest types of another LiDAR will also be evaluated
  - Evaluation of 2D PCSEL-LiDAR
    - Testing PCSEL-LiDAR developed in SIP Phase 2 in outdoor environments

Velodyne（Ouster）VLS-128AP

Contents	Sensor specification
Range	300m@10% targets
Resolution	Horizontal 0.2° @10Hz Vertical 0.11～5°
Field of View（FOV）	Horizontal360° , Vertical 40°



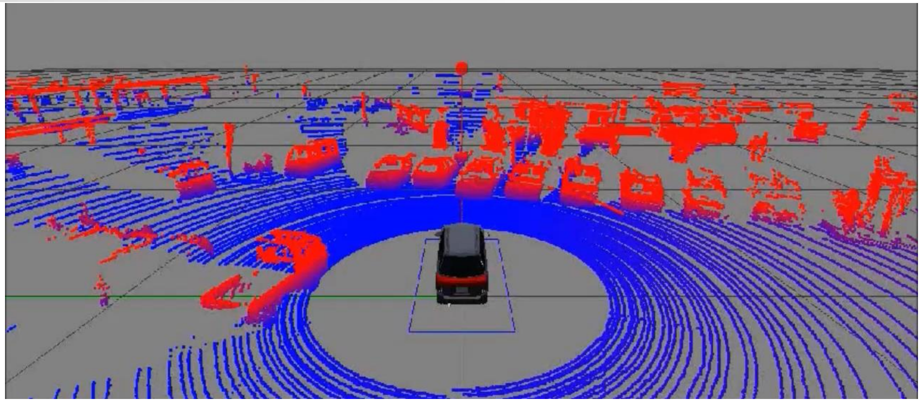
2D PCSEL-LiDAR

*DNN: Deep Neural Network

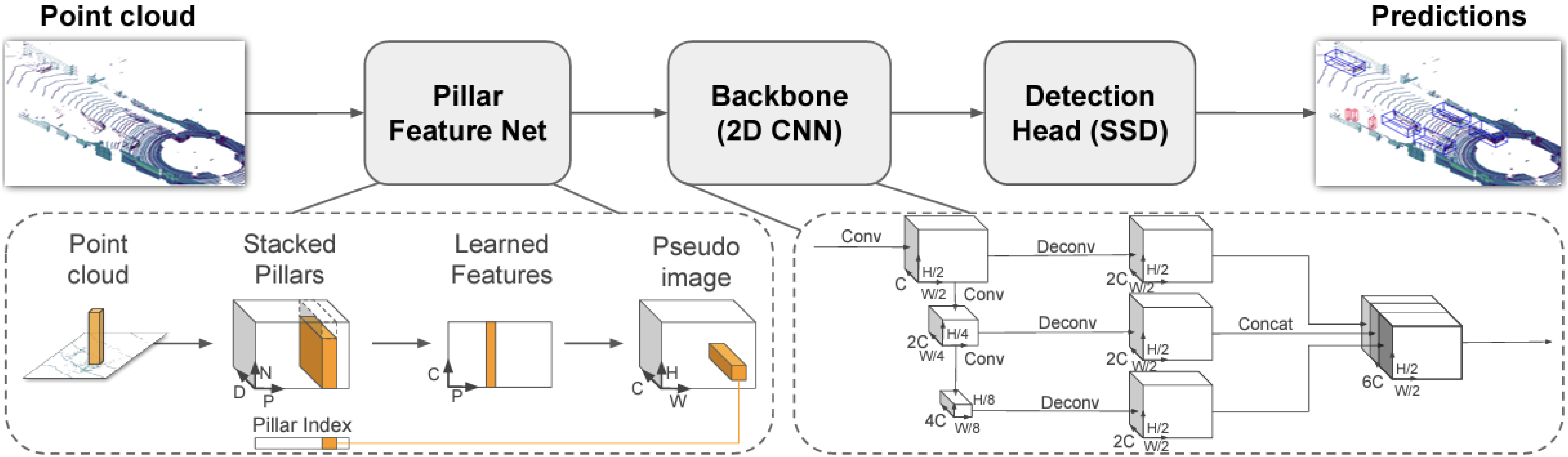
Implementation of LiDAR Object Detection Model

- 3D object detection using LiDAR
  - Detecting traffic participants as bounding box
    - Vehicles, pedestrians, cyclists, etc.
- Implementation of basis object detection DNN model
  - Representative model：PointPillars [A. H. Lang, et al., 2018]
    - DNN* model detecting arbitrary number of 3D boxes in LiDAR point cloud

*Deep Neural Network

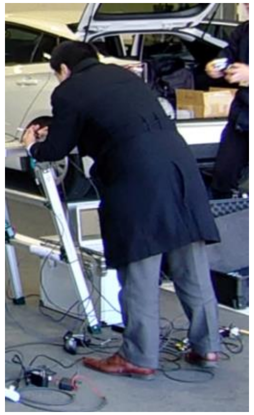


Point cloud obtained from 3D LiDAR

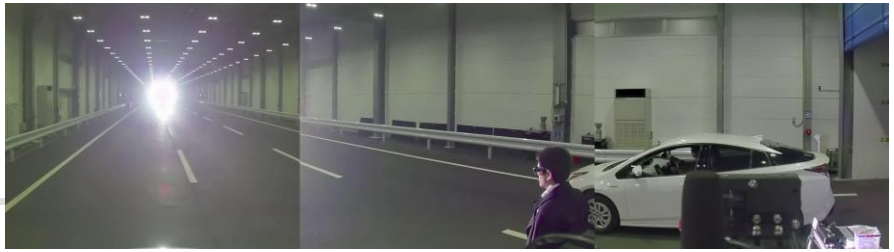


Evaluation test at JARI's test facility

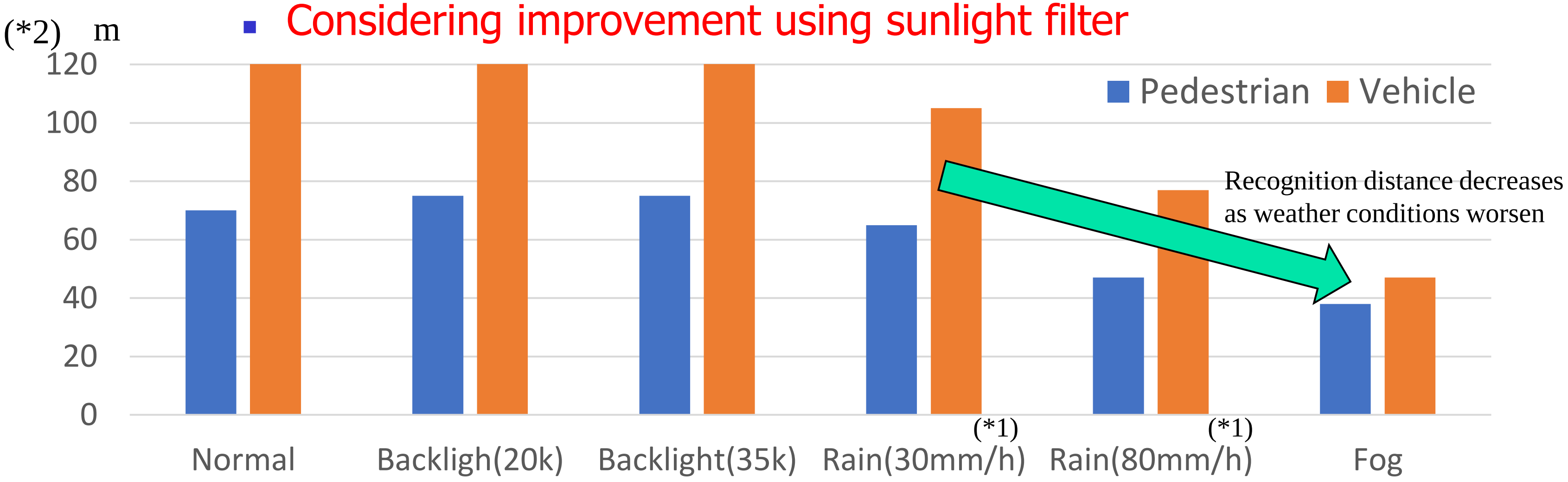
- Conditions
  - Normal (indoor environment under fluorescent lighting)
  - Backlight： Sunlight equivalent to 3:00PM and 5:00PM on fine day
    - Illuminance: 35,000lux（3:00PM）, 20,000lux（5:00PM）
    - Color temperature：6000K（daylight white）, 2000K（amber white）
  - Rainfall： Rates of 30 and 80mm/h
  - Fog：Visibility distance of 50m
- Measurement targets
  - Vehicle： White Prius
  - Pedestrian： wearing a black coat, raincoat
- Evaluating detectable distance using LiDAR object detection model

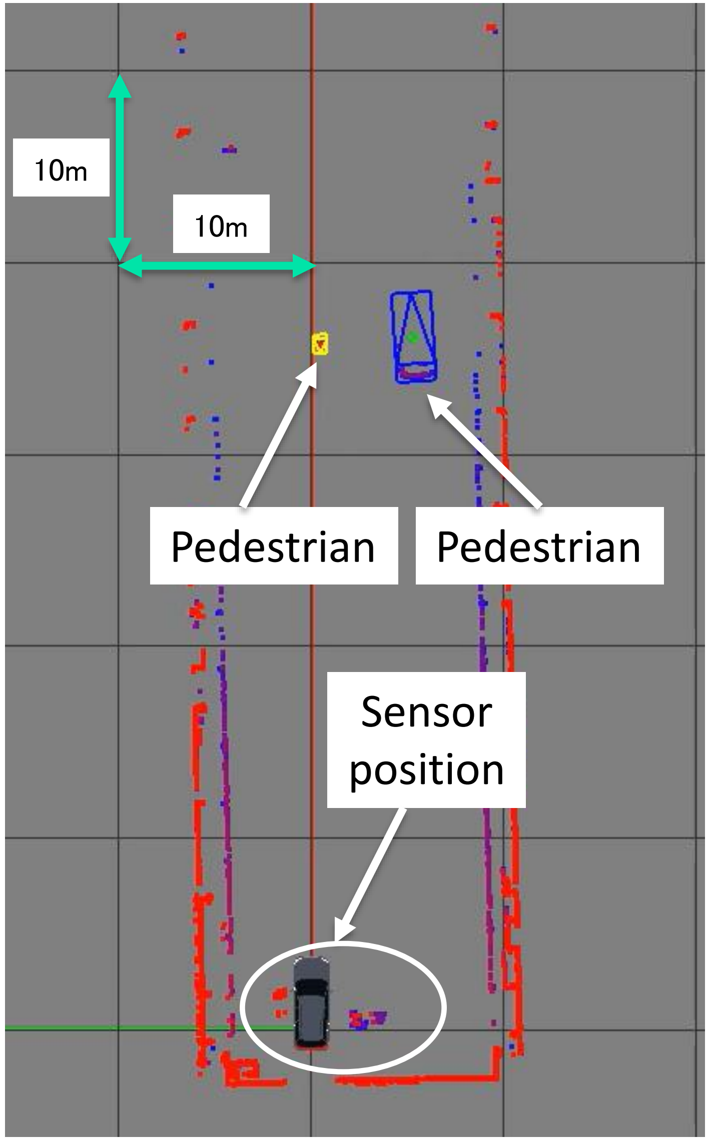


Evaluation Results of Existing LiDAR



- Evaluation of recognition distance of 3D LiDAR（Velodyne VLS-128）
  - Normal and backlight conditions
    - Detecting vehicle over 120m and pedestrian up to approximately 70m
    - Low dependency on backlight
  - Bad weather conditions like rain and fog
    - Tendency to decrease recognition distance
- Current issue of 2D PCSEL-LiDAR
  - Phenomenon of point cloud data affected by westering sun
    - Considering improvement using sunlight filter





(*1) Setting value of test facility (*2) Limitation of maximum distance at test facility

Progress Schedule

Working Items			Schedule (2023 Q1 – 2027 Q4)
① Development of 3D PCSEL-LiDAR system	STEP1. 「Development of wide-FOV 3D PCSEL-LiDAR」	Improvement and fabrication of vertical-emission-type PCSEL	2023 Q3 – 2024 Q2: TRL5~6, TRL7
		Design and prototyping of wide-FOV 3D PCSEL-LiDAR	2023 Q3 – 2025 Q2: TRL2~3, TRL5~6; 2026 Q2 – 2026 Q4: TRL7
	STEP2. 「Development of non-mechanical 3D PCSEL-LiDAR」	Design, fabrication, and deepening of multi-dot emission-type PCSEL	2023 Q3 – 2026 Q4: TRL3~4, TRL5, TRL6, TRL7
		Procurement of SPADs and development of a control unit	2023 Q3 – 2026 Q4: TRL2~3, TRL4~5, TRL6, TRL7
		Design and development of PCSEL driving circuit	2023 Q3 – 2027 Q1: TRL2, TRL3~4, TRL5~6, TRL7
		Design and prototyping of nonmechanical 3D PCSEL-LiDAR	2023 Q3 – 2027 Q4: TRL2, TRL3~4, TRL5~6, TRL7
Additional item	Development of card-type LiDAR	Prototyping of card-type wide-FOV 2D PCSEL-LiDAR	2023 Q3 – 2024 Q3: TRL2, TRL5~6
② Development of recognition technology and conducting field-operational test	A. 「Development of recognition technology using LiDAR」	Survey of the latest recognition algorithms	2023 Q3 – 2023 Q4: TRL2~3
		Building a virtual sensing environment	2024 Q1 – 2024 Q4: TRL3~4
		Development of recognition algorithms with small-scale computing devices	2025 Q1 – 2025 Q4: TRL5
		Improvement of recognition models for expanding detection range	2026 Q1 – 2026 Q4: TRL5~6
		Construction of recognition models cooperated with infrastructure and on-vehicle sensors	2027 Q1 – 2027 Q4: TRL7
	B. 「Field-operational test (FOT) using LiDAR」	Evaluation of existing LiDAR sensor	2023 Q3 – 2023 Q4: TRL1~2
		Public road experiment with existing LiDAR sensor	2023 Q3 – 2025 Q2: TRL4~5, TRL5~6
		FOT with wide-FOV LiDAR as infrastructure sensor	2025 Q3 – 2025 Q4: TRL5
		FOT with wide-FOV LiDAR as on-vehicle sensor	2025 Q3 – 2026 Q4: TRL5~6
		Construction of test vehicles equipped with multiple PCSEL-LiDAR, etc.	2025 Q1 – 2026 Q4: TRL5~6
		FOT cooperated with infrastructure sensors and on-vehicle sensors	2027 Q1 – 2027 Q4: TRL7

R&D Items & Roadmap

Collaboration with other projects

Results of SIP Phase 2

Infrastructure co-ordination demonstration

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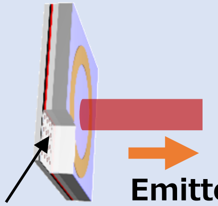
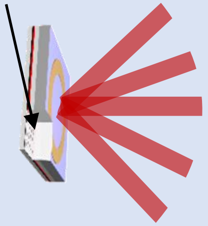




Photonic crystal laser (PCSEL)

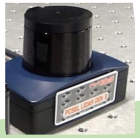
京都大学 KYOTO UNIVERSITY PCSEL-COE

Field-operational test (FOT) by Kanazawa University

② Development of recognition technology and conducting field-operational test

Evaluation of applicability of PCSEL-based 2D LiDAR (SIP Phase 2)

Evaluation of applicability of 2D PCSEL-LIDAR

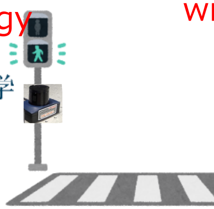


PCSEL-based 2D LiDAR

Additional item: Prototyping of 2D card-type PCSEL-LiDAR for inter-project collaboration scheduled for end of December 2024

(Note) Specifications of card-type LiDAR to be decided by October 2024

② A. Development of recognition technology



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② B. Field-operational test (FOT) of infrastructure sensing

① STEP-1. Development of wide-FOV 3D PCSEL-LiDAR

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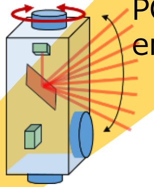
Operation test of wide-FOV 3D PCSEL-LiDAR

Test of wide-FOV 3D PCSEL-LiDAR prototype



Prototyping of wide-FOV 3D PCSEL-LiDAR: Scheduled for end of September 2025

(Note) Specifications of wide-FOV LiDAR to be decided by March 2025

② B. Field-operational test (FOT) of on-board sensor

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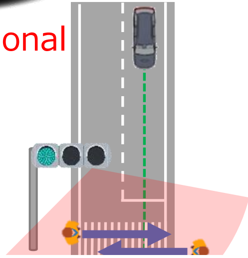
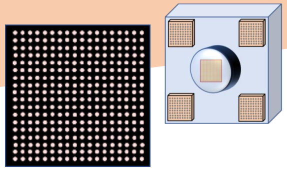


② B. Conduction of a level-4 equivalent demonstration that co-ordinates infrastructure and on-board sensing

Operation test of non-mechanical 3D PCSEL-LiDAR prototype

Prototyping of non-mechanical 3D PCSEL-LiDAR



① STEP-2. Development of nonmechanical 3D PCSEL-LiDAR

(Start with a separated PCSEL/SPAD configuration)

Kyoto University & Ecosystem + Hokuyo Automatic

① Development of 3D PCSEL-LiDAR system

Design of light source for 3D PCSEL-LiDAR

Fabrication of light source for 3D PCSEL-LiDAR

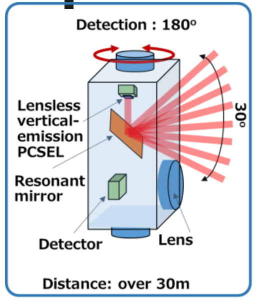
Development of 3D PCSEL-LiDAR for innovation of smart mobility

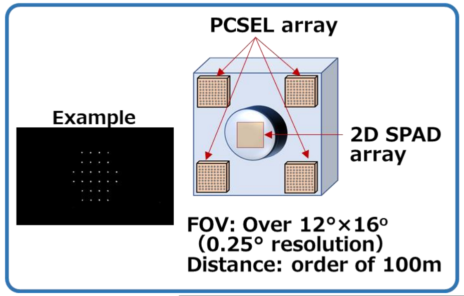
京都大学 KYOTO UNIVERSITY PCSEL-COE

SIP Phase 3

Year 1	Year 2	Year 3	Year 4	Year 5

Implementation Structure





NEDO

Instructions & Discussion ↔

Head of R&D
- Affiliation: Kanazawa University Advanced Mobility Research Institute
- Title: Vice-director, Professor
- Name: Naoki Suganuma

Commissioning ↓

Kyoto University
(① Development of 3D PCSEL-LiDAR system) Susumu Noda, Menaka De Zoysa, and others

PCSEL-LiDAR development →

← Feedback from demonstration

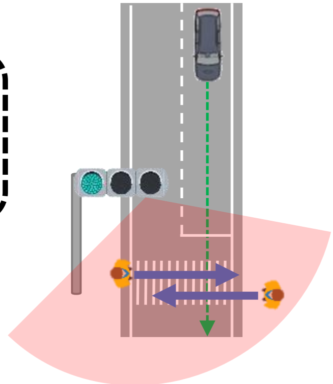
Kanazawa University
(② Development of recognition technology and conducting Field-operational test) Naoki Suganuma, Keisuke Yoneda, and others

Recommissioning ↓

Hokuyo Automatic
Construction and basic evaluation of LiDAR system Naohiro Shimaji and others

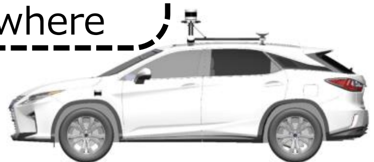
Collaboration ↓

Fraunhofer (International collaborator)
PCSEL-COE ecosystem



Proof-of-concept demonstrations ↓

<Demonstration sites>
- Tokyo waterfront area (Odaiba)
- Kanazawa City, Ishikawa Prefecture
- Abashiri City, Hokkaido, and elsewhere



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