3D Sensor Data Processing Curriculum

SLAM KR

No.	Title	Content	Date	Speaker
01	3D Point Cloud	• 3D Point Clouds • Point Cloud Processing • Datasets	08.13	이용이 (SOSLAB)
02	3D Data Acquisition (Passive)	• Stereo Vision • Photogrammetry & Multiview Geometry	08.20	박준휘 (MagicLeap)
03	3D Data Acquisition (Active)	• RGB-D Camera • LiDAR	08.20	함승록 (LG전자)
04	Differential Geometry	• Differential Geometry	08.27	장승호 (MORAI)
05	Spatial Transformation	• Spatial Transformation	08.27	이용이 (SOSLAB)
06	Point Cloud Analysis #1	• Filtering • Nearest Neighbor Search	09.03	길현재 (서울대학교)
07	Point Cloud Analysis #2	• Model Fitting • Point Cloud Features	09.03	윤형석 (CMES)
08	Point Cloud Analysis #3	• Classification and Segmentation • Registration	09.10	최재우 (PLAIF)
09	Point Cloud Analysis #4	• Clustering	09.10	신동훈 (SOSLAB)
10	Point Cloud Analysis #5	• Deep Learning on Point-cloud	09.17	이종록 (VUERON Technology)
11	Point Cloud Analysis #6	• Communication • Visualization	09.17	이상운 (Seoul Robotics)
12	PCD Tools	• PCL • Open3D • CloudCompare	09.24	최준호 (SOSLAB)

3D Data Acquisition (Active)

2023. 08. 27

함 승 록 (hihihama@gmail.com)

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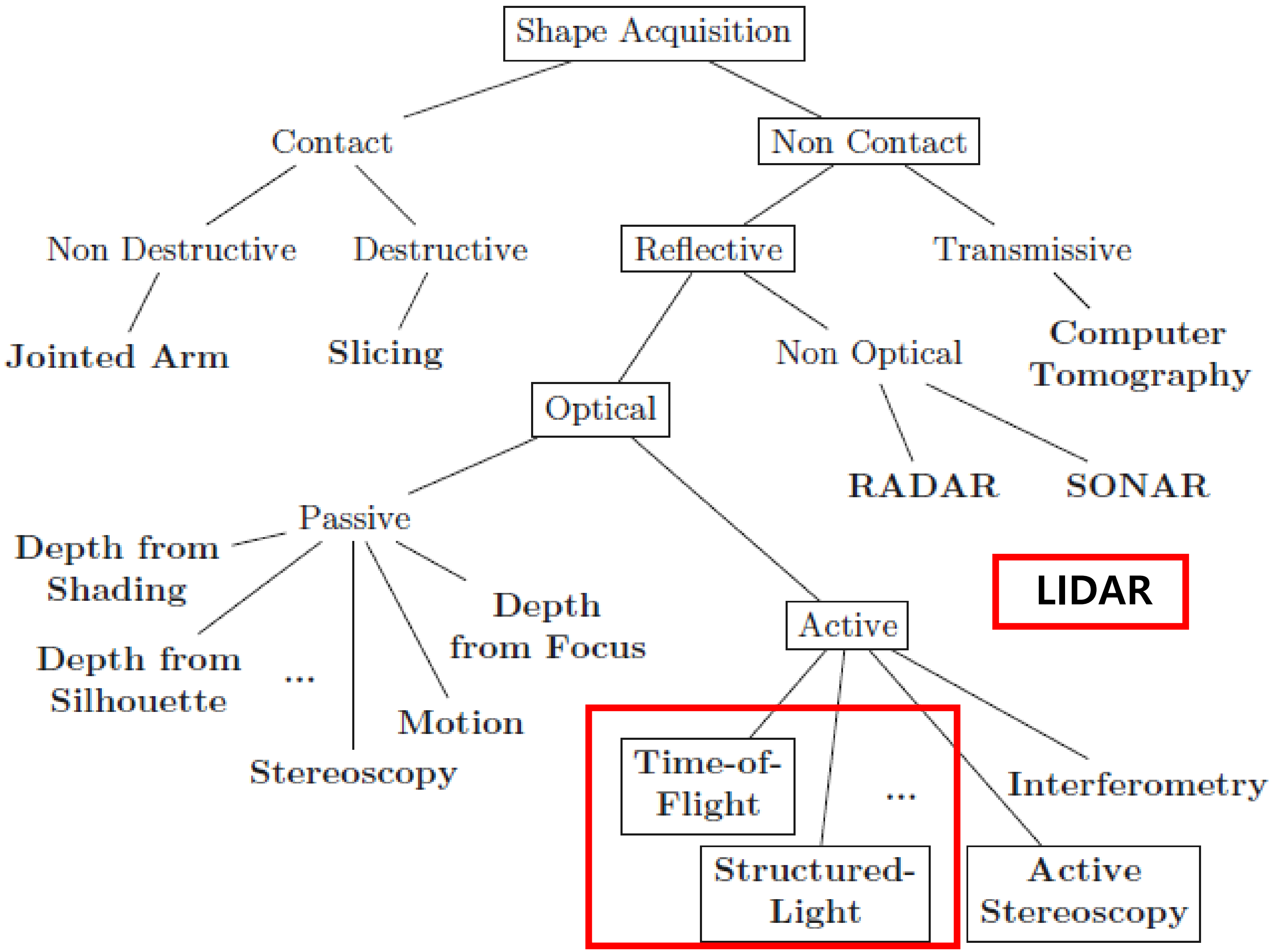
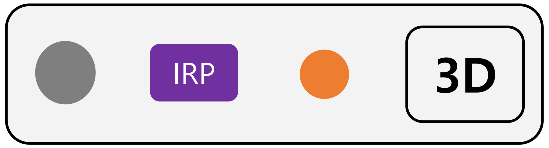
Introduction



[Ref] A Survey on 3D Cameras: Metrological Comparison of Time-of-Flight, Structured-Light and Active Stereoscopy Technologies

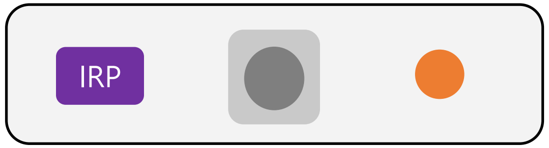
Overview of RGB-D Camera Sensor

▪ RGB-D Camera Type



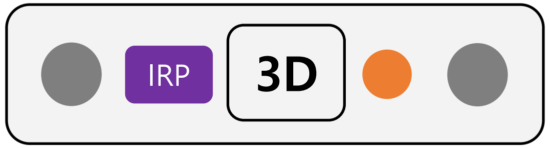
< Structed-Light >

- Kinect V1
- Apple



< Time of Flight >

- Infineon
- Sony
- Samsung



< Hybrid Stereo >

- Intel

IR Image Sensor

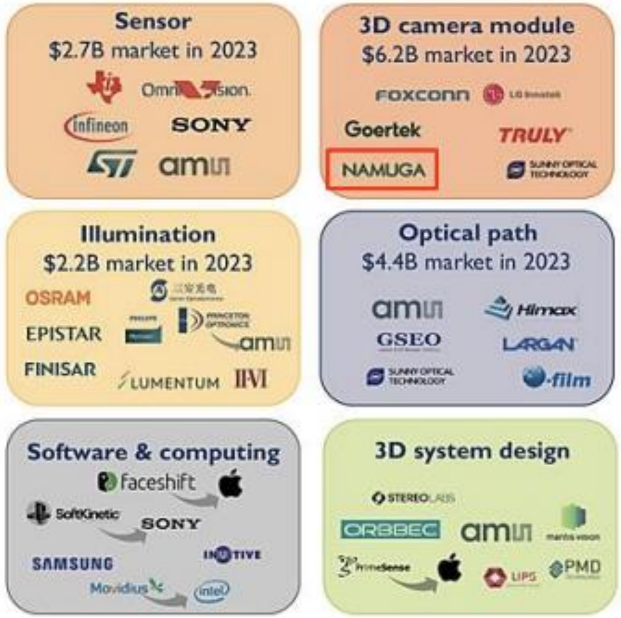
RGB Image Sensor

ToF Depth Sensor

3D 3D Image Processor

IRP IR Laser Projector

▪ 3D Sensing Key Player & History



Source) Yole Development, June 2018

- Kinect v1 출시 (2011)
- Apple이 PrimeSense 인수 (2013)
- iphone X 출시 – FaceID (2017)
- Intel Realsense D400 Family출시 (2018)
- SmartPhone에 3D Depth Module이 들어가면서, 시장이 증가

Size↓, Cost↓

[Ref] Namuga https://file.irgo.co.kr/data/BOARD/ATTACH_PDF/DXC737XT896X9F5JU6UBGKVM74PJSH8Q2019717833.pdf

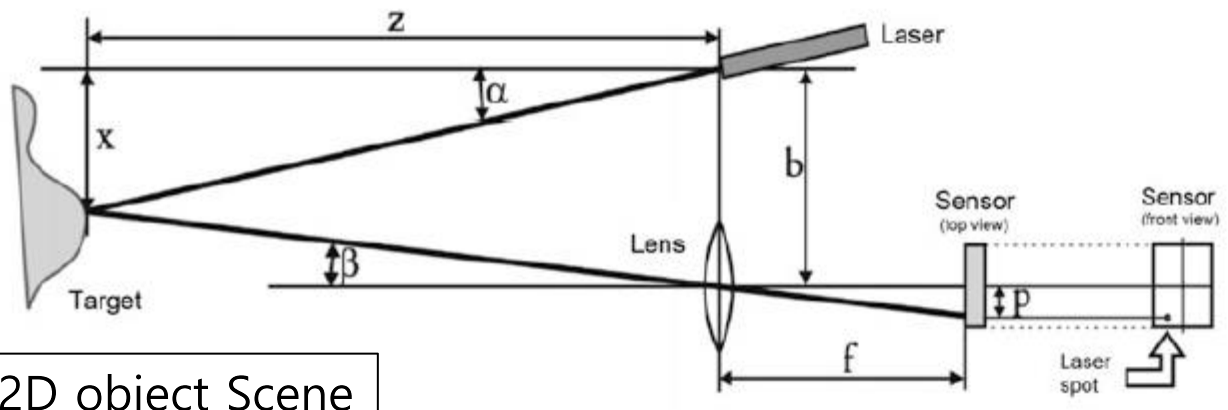
3D Shape Acquisition (Structed-Light)

- **Structed-Light**
  - Single camera with a structured pattern projected in the scene
  - Instead of triangulating with two cameras, a camera is substituted by a laser projector
  - Codified pattern that embed enough structure to provide unique correspondences to triangulate with the camera
  - The direction of the structured pattern is known a priori by the camera, which is able to triangulate based on the pattern

$$\tan(\alpha) = \frac{x}{z} \quad \cdots (1)$$

$$\tan(\beta) = \frac{b - x}{z} \quad \cdots (2)$$

$$\boxed{z = \frac{b}{\tan(\alpha) + \tan(\beta)}} \quad \cdots (1) + (2)$$



2D object Scene

Fig. 2.14 Triangulation with a single laser spot

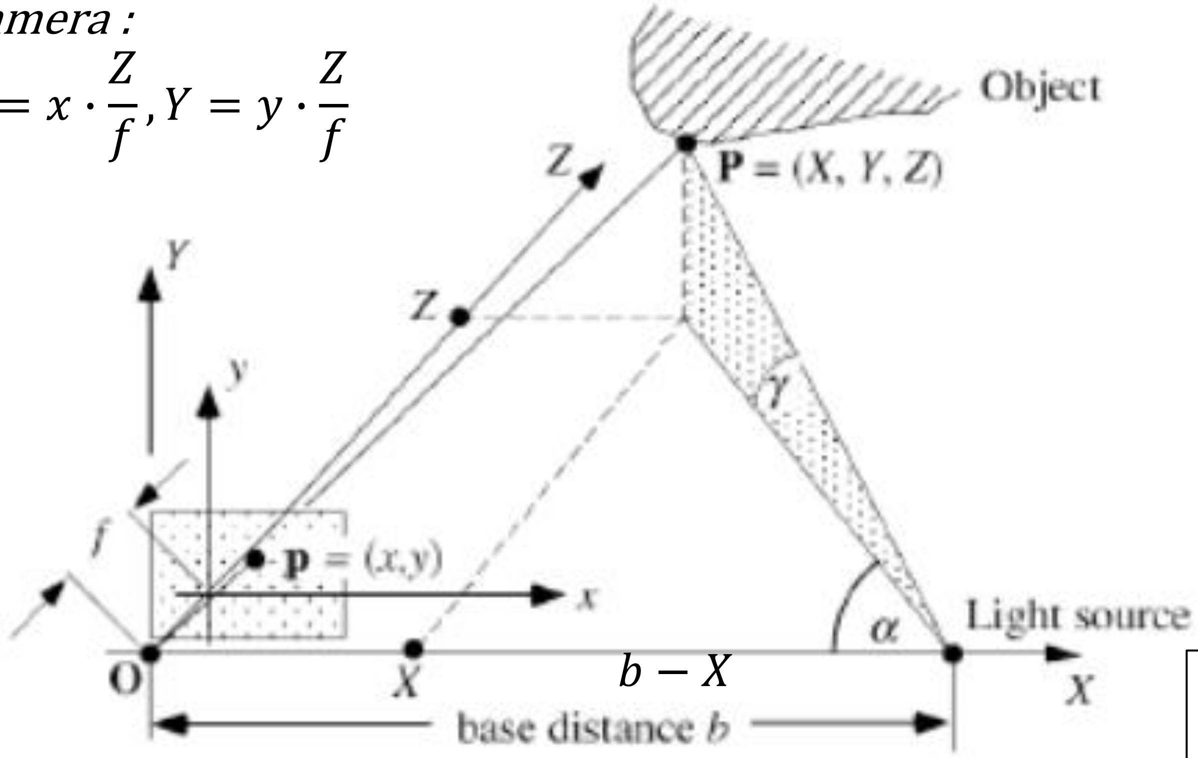
3D Shape Acquisition (Structed-Light)

- **Structed-Light**
  - The object point P=(X ,Y ,Z) is projected onto a point p=(x,y) in the image plane

3D object Scene

Camera :

$$X = x \cdot \frac{Z}{f}, Y = y \cdot \frac{Z}{f}$$



$$\tan(\alpha) = \frac{Z}{b - X}$$

$$Z = \frac{X \cdot f}{x} = \tan(\alpha) \cdot (b - X)$$

$$X \cdot \left(\frac{f}{x} + \tan(\alpha)\right) = \tan(\alpha) \cdot b$$

$$X = \frac{\tan(\alpha) \cdot b \cdot x}{\left(\frac{f}{x} + \tan(\alpha)\right) \cdot x}$$

$$\boxed{X = \frac{\tan(\alpha) \cdot b \cdot x}{f + x \cdot \tan(\alpha)}, \mathrm{Y} = \frac{\tan(\alpha) \cdot b \cdot y}{f + x \cdot \tan(\alpha)}, \mathrm{Z} = \frac{\tan(\alpha) \cdot b \cdot f}{f + x \cdot \tan(\alpha)}}$$

[Ref] https://www.youtube.com/watch?v=3S3xLUXAgHw, https://www.sci.utah.edu/~gerig/CS6320-S2013/Materials/CS6320-CV-S2012-StructuredLight.pdf

3D Shape Acquisition (Structed-Light)

- **Structed-Light**
  - Laser Blade
    - Instead of a single dot, a laser plane intersects the shape to reconstruct
    - The laser blade in the image and perform a triangulation for each point of the line
  - Time-Multiplexing
    - The most common strategy when it comes to early structured-light
    - Do not allow for dynamic shape reconstruction
  - Spatial Neighborhood
    - Spatially-structured pattern that creates uniqueness in the neighborhood of each projected pixel

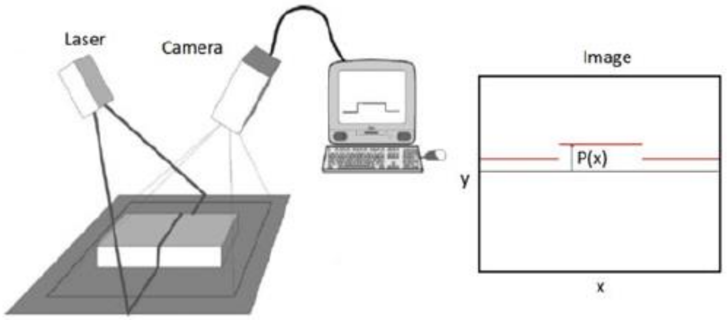


Fig. 2.15 Triangulation with a laser blade

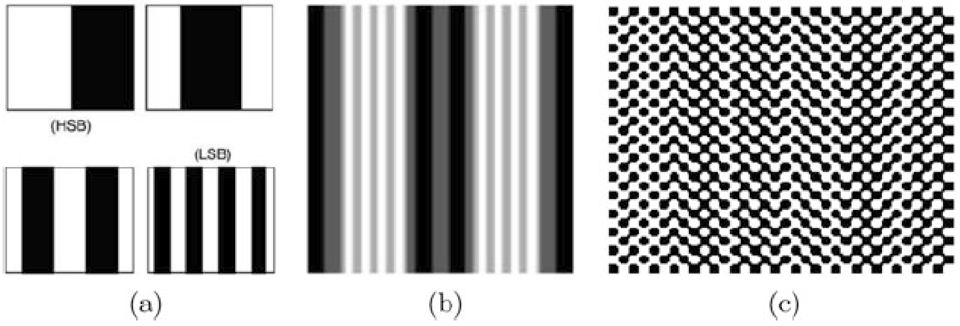


Fig. 2.16 *From left to right*: time-multiplexing strategy, direct coding and spatial neighborhood

3D Shape Acquisition (Structed-Light)

- **Structed-Light**
  - Kinect V1

    https://www.youtube.com/watch?v=dTKlNGSH9Po
  - Apple iphone X

    https://www.youtube.com/watch?v=g4m6StzUcOw

< Kinect V1 >

< iphone X >

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - The TOF principle can directly estimate the device-target distance
  - The core of an optical Time-of-Flight system consists of a light transmitter and a receiver
  - The round-trip time from the transmitter to the receiver is an indicator of the distance of the object
  - Integrated systems measures distances exploiting the TOF principle use either **pulsed-modulation** or **Continuous-Wave (CW) modulation**

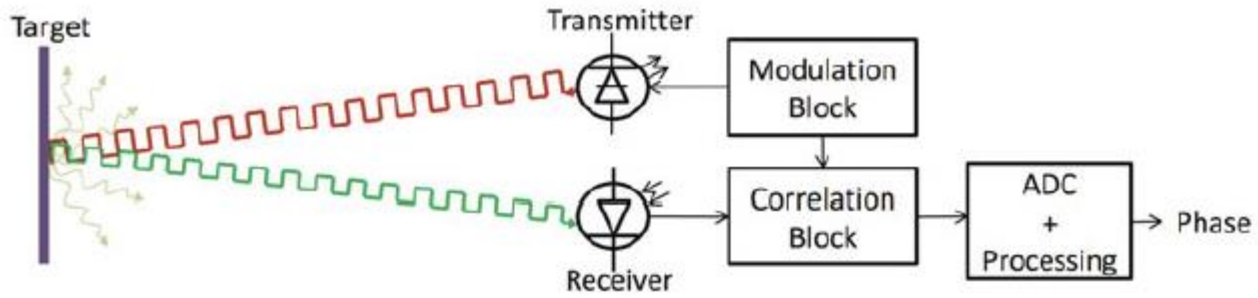


Fig. 2.17 Time-of-Flight emission, reflection and reception principle

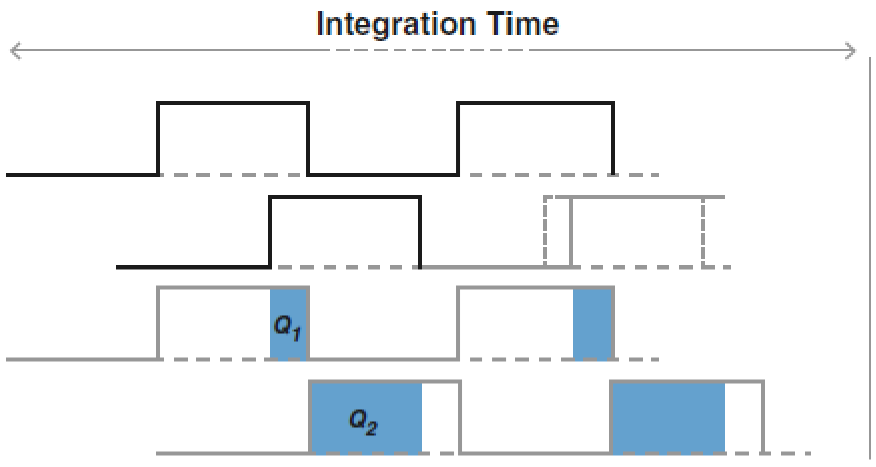
$$\boxed{d = \frac{c * \Delta t}{2}}$$

c : *light speed*
Δt : *time delay*

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - Pulse-modulation
    - It requires very short light pulses with fast rise- and fall-times, as well as high optical power like lasers or laser diodes
    - It estimates the delay as the ratio of photons Q2 that strikes back C2 respect to the total energy Q1 + Q2 that strikes back both C1 and C2

$$d = \frac{c * t_{int}}{2} \cdot \frac{Q_2}{Q_1 + Q_2}$$



Light Source

Reflection

C1 In Phase

C2 Out of Phase

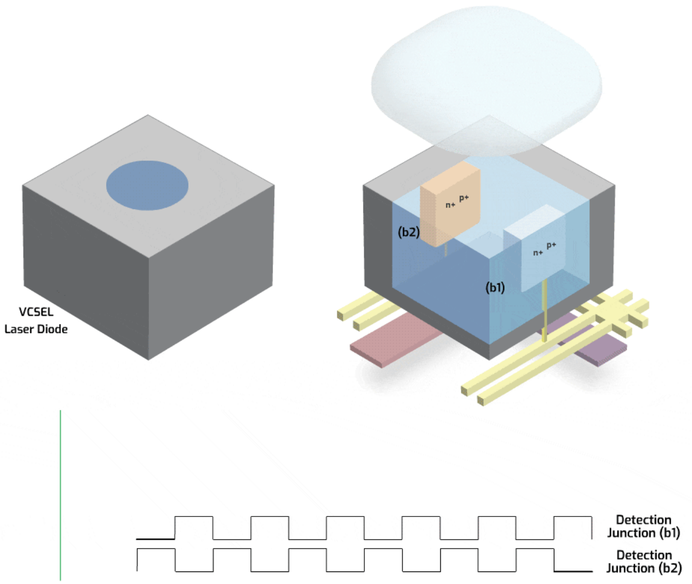
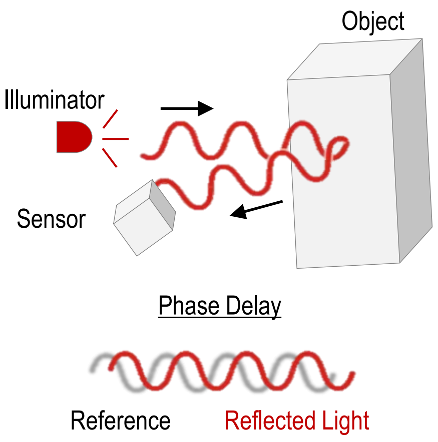


Fig. 2.19 Pulsed-modulation method from Li (2014)

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - Continuous-Wave (CW) modulation
    - A cross-correlation operation between the emitted and the received signal to estimate the phase between the two signals
    - This operation also takes into account multiple samples hence provides **improved precision**



$$\boxed{d = \frac{c * \Delta t}{2} \quad \text{with} \quad \Delta t = \frac{\phi}{2\pi f}}$$

ϕ …… 위상 각

f …… 각속도

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - Continuous-Wave (CW) modulation
    - The four-bucket technique that takes into consideration four samples of the emitted signal, phase-stepped by 90◦
    - Electrical charges from the reflected signal accumulates during these four samples and the quantity of photons are probed in Q1, Q2, Q3 and Q4

$$\boxed{d = \frac{c}{4\pi f}\phi \quad \text{with} \quad \phi = \operatorname{atan}\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right)}$$

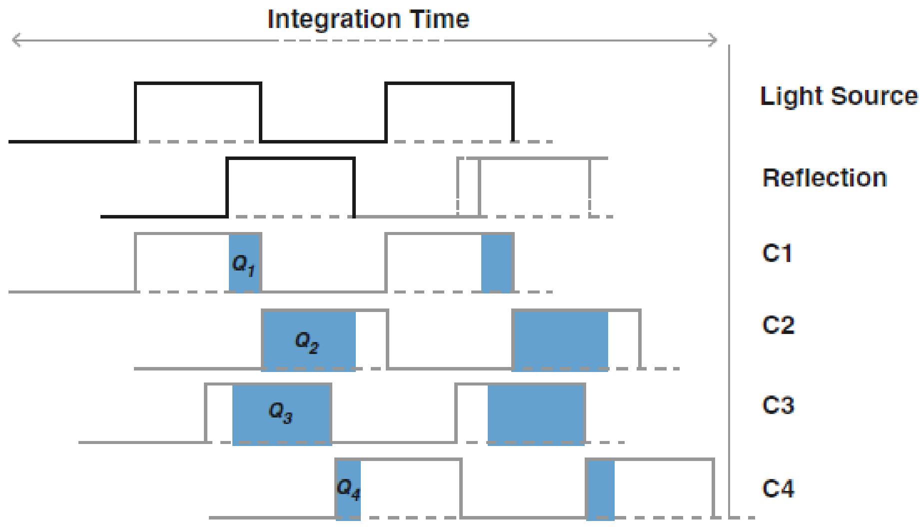


Fig. 2.20 Four phase-stepped samples according to Wyant (1982)

[Ref] A Survey on 3D Cameras: Metrological Comparison of Time-of-Flight, Structured-Light and Active Stereoscopy Technologies

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - Continuous-Wave (CW) modulation
    - Let s(t) and r(t) be the optical powers of the emitted and received signals respectively

$$s(t) = a_1 + a_2 \cos(2\pi f t),$$
$$r(t) = A \cos(2\pi f t - 2\pi f \tau) + B,$$

$a1, a2$: *offset and amplitude of emitted signal*
f : *modulation frequency*
τ : *time delay between the emitted and received signal*
A, B : *amplitude and offset of received signal*

    - The cross-correlation between the powers of the emitted and received signals can be written as:

$$\boxed{\mathcal{C}(x) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} s(t) r(t-x) \mathrm{d}t.}$$

$\downarrow$ ⋯ (1)

$$\begin{aligned}\mathcal{C}(x,\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} \Big(& a_2 B \cos(2\pi f t) \\ & + a_2 A \cos(2\pi f t) \cos(2\pi f t - 2\pi f(\tau + x)) \\ & + a_1 A \cos(2\pi f t - 2\pi f(\tau + x)) \Big) \mathrm{d}t \\ & + a_1 B.\end{aligned}$$

⋯ (2)

$$\lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} \cos t \,\mathrm{d}t = 0$$

$$\lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} \cos t \cos(t-u) \,\mathrm{d}t = \frac{1}{2} \cos u,$$

$$\mathcal{C}(x,\tau) = \frac{a_2 A}{2} \cos(2\pi f (x + \tau)) + a_1 B.$$

$$\psi = 2\pi f x \text{ and } \phi = 2\pi f \tau,$$

$$\boxed{\mathcal{C}(\psi,\phi) = \frac{a_2 A}{2} \cos(\psi + \phi) + a_1 B.}$$

3D Shape Acquisition (Time of Flight)

- **Time of Flight**
  - Continuous-Wave (CW) modulation
    - Let's consider the values of the correlation function at four equally spaced samples within one modulation period, ψ0 = 0, ψ1 = π/2, ψ2 = π, and ψ3 = 3π/2, namely C0 = C(0, Φ), C1 = C(π/2, Φ), C2 = C(π, Φ), and C3 = C(3π/2, Φ)

$$C_0 = \frac{a_2 A}{2}\cos(\phi) + a_1 B$$

$$C_1 = \frac{a_2 A}{2}\cos\left(\frac{\pi}{2} + \phi\right) + a_1 B \;\rightarrow\; C_1 = -\frac{a_2 A}{2}\sin(\phi) + a_1 B$$

$$C_2 = \frac{a_2 A}{2}\cos(\pi + \phi) + a_1 B \;\rightarrow\; C_2 = -\frac{a_2 A}{2}\cos(\phi) + a_1 B$$

$$C_3 = \frac{a_2 A}{2}\cos\left(\frac{3\pi}{2} + \phi\right) + a_1 B \;\rightarrow\; C_3 = \frac{a_2 A}{2}\sin(\phi) + a_1 B$$

$$C_0 - C_2 = a_2 A\cos(\phi) \quad \cdots (1)$$

$$C_3 - C_1 = a_2 A\, sin(\phi) \quad \cdots (2)$$

$$\frac{C_3 - C_1}{C_0 - C_2} = \frac{a_2 A\, sin(\phi)}{a_2 A\cos(\phi)} \quad \cdots (3)$$

$$\boxed{\begin{aligned} \phi &= \arctan\left(\frac{C_3 - C_1}{C_0 - C_2}\right) \\ A &= \frac{1}{a_2}\sqrt{(C_3 - C_1)^2 + (C_0 - C_2)^2} \\ B &= \frac{1}{4a_1}(C_0 + C_1 + C_2 + C_3) \end{aligned}}$$

[Ref] An Overview of Depth Cameras and Range Scanners Based on Time-of-Flight Technologies

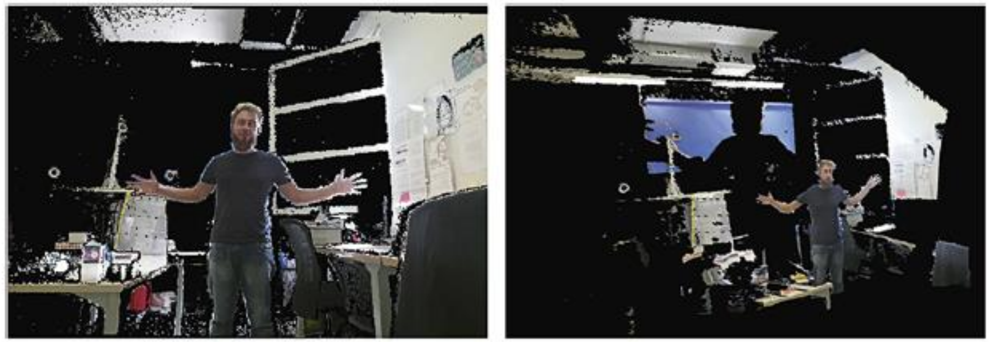
3D Shape Acquisition (Depth Map to Point Cloud)

- **Depth Map to Point Cloud**
  - Distance measurements, a minimum of information about the intrinsic parameters are necessary such as focal length, optical center and distortion
  - RGB-D cameras usually perform it independently and provide range maps along the optical axis
  - A 3D point (X, Y, Z) is obtained from the depth information Dx,y, (x, y) being the rectified pixel position on the sensor

$$
\begin{aligned}
X &= \mathbf{D}_{x,y} * (c_x - x)/\mathbf{f}_x \\
Y &= \mathbf{D}_{x,y} * (c_y - y)/\mathbf{f}_y \\
Z &= \mathbf{D}_{x,y}
\end{aligned}
$$

(a) Depth Frame (b) Point Cloud

Fig. 2.25 Point cloud (**b**) obtained from the depth map (**a**)



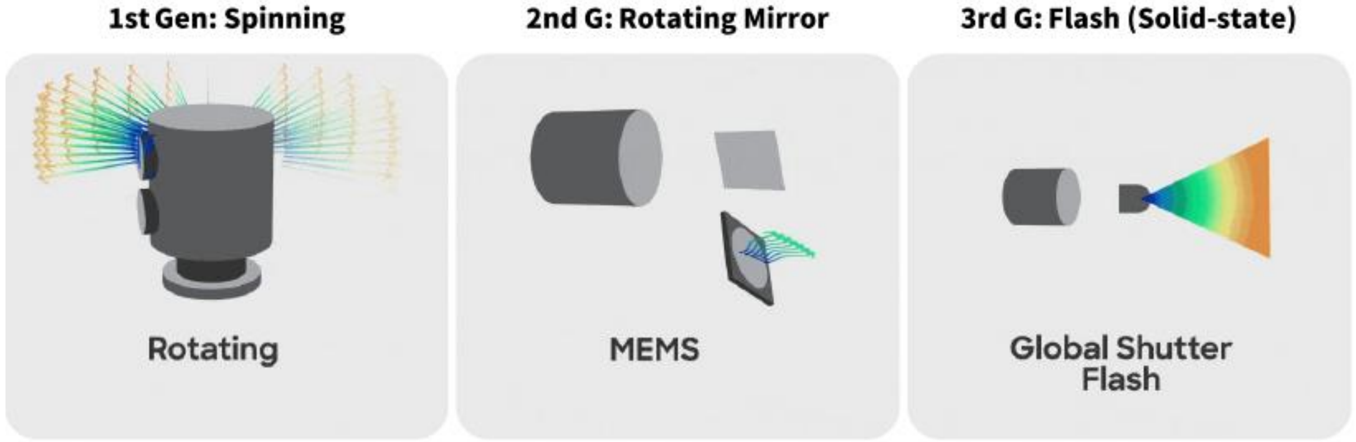
(a) Colored depth frame (b) Colored point cloud

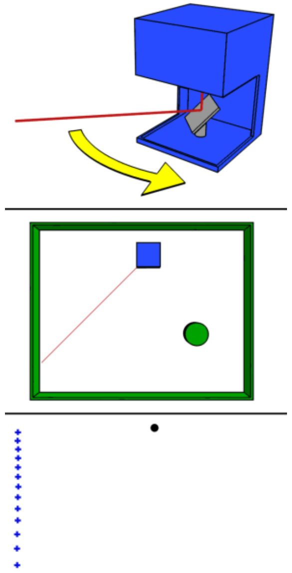
Fig. 2.26 Color Point cloud (**b**) obtained from the colored depth map (**a**)

[Ref] A Survey on 3D Cameras: Metrological Comparison of Time-of-Flight, Structured-Light and Active Stereoscopy Technologies

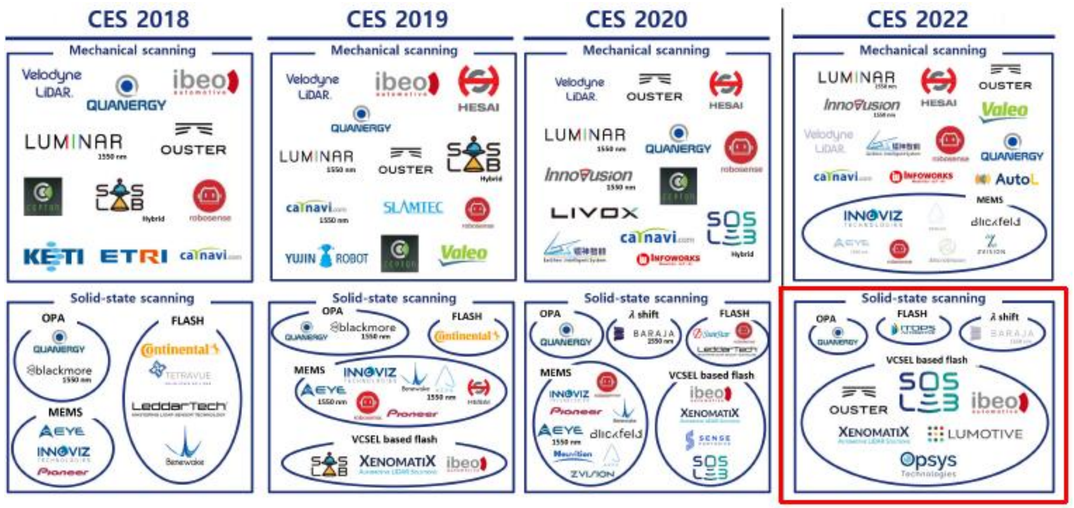
Overview of Lidar Sensor

- **Lidar Sensor Type**





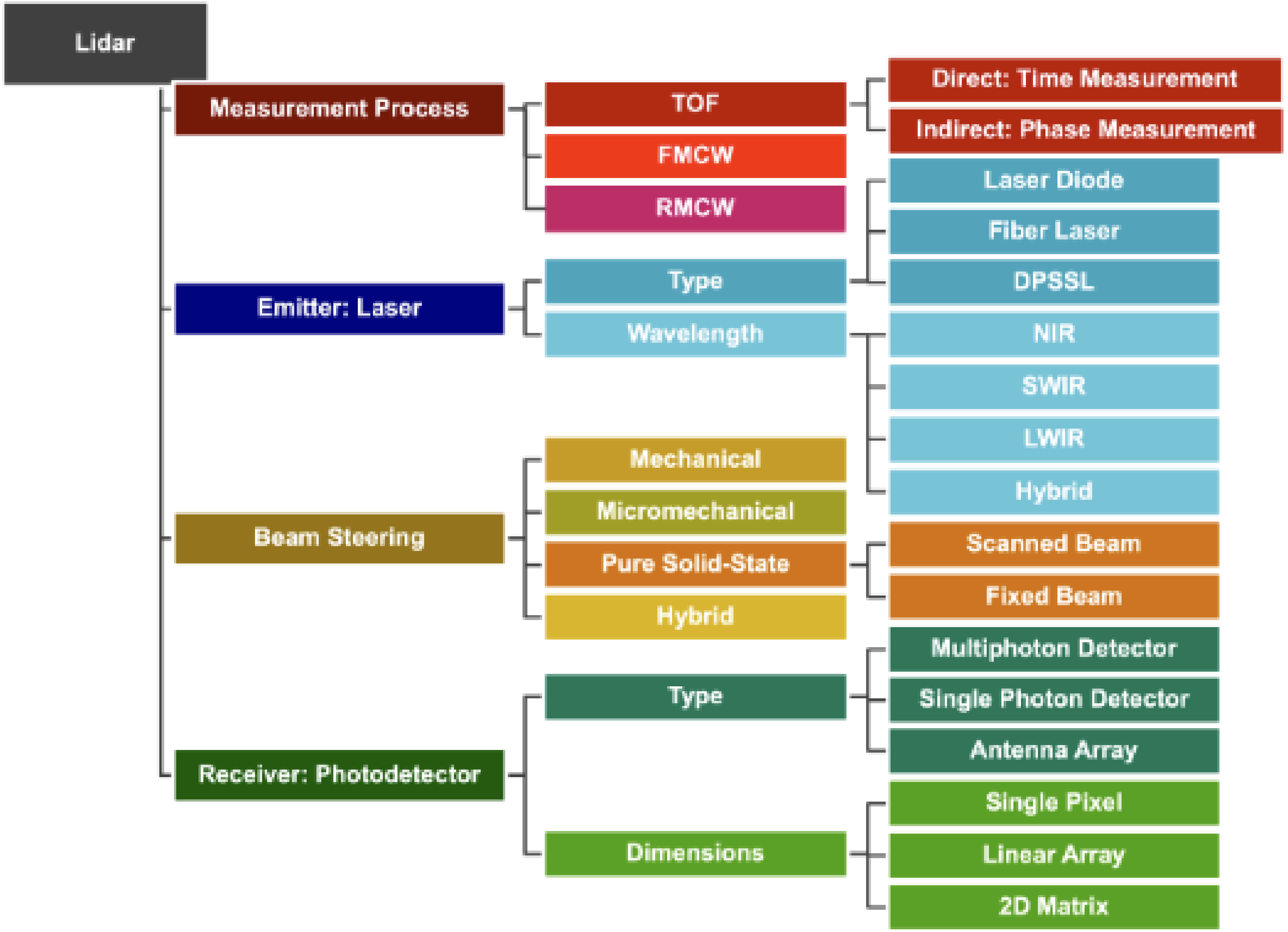
- **Lidar Key Player & History**



	1930년대	1950년대	1980년대	1990년대	2000년대	현재
주요이슈 기술	탐조등 빛의 세기를 통한공기 밀도분석	레이저의 본격적 개발	레이저 고도계 시스템 개발	거리측정용 레이저	카메라 기능 보완용	레이저 스캐너 및 3D 기술
적용분야 제품	공기밀도 분석	위성, 해양 및 대기 관측	대기 해양 라이다 및 맵핑	항공기, 위성 탑재 정밀 대기 분석	우주선 및 로봇 적용 자동차 속도 측정	자율주행 및 무인이동체 적용

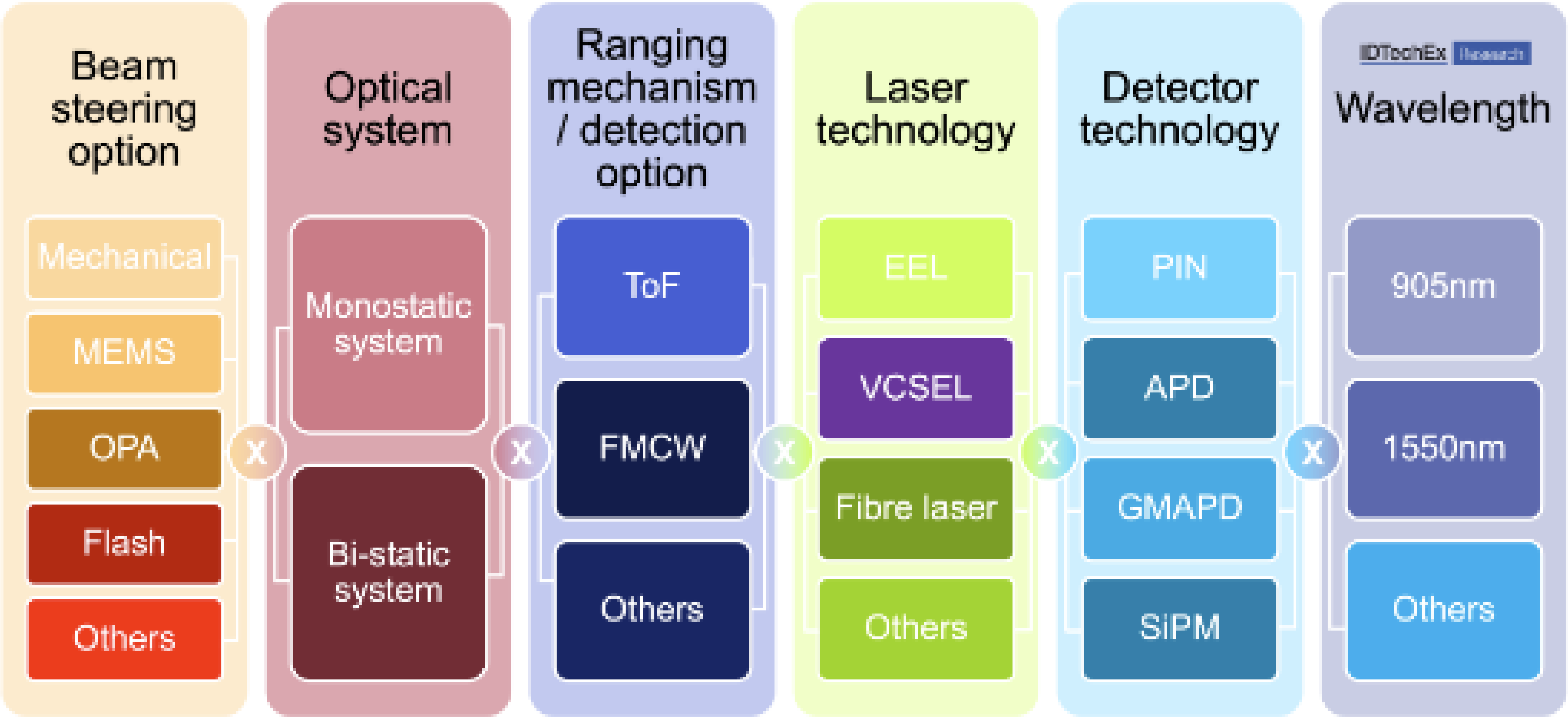
라이다 센서의 발전 과정

Lidar Sensor 핵심 기술



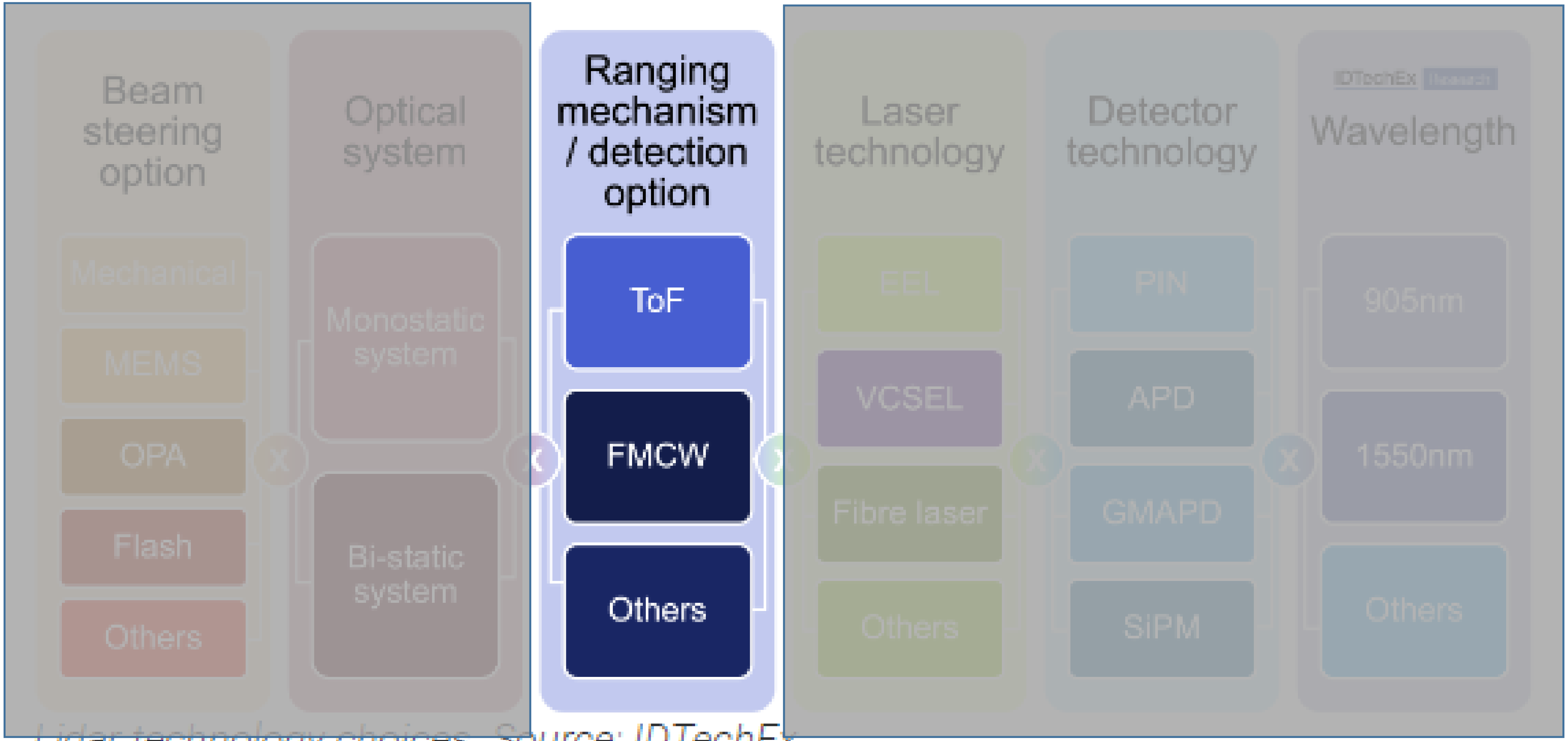
Four important technology choices in designing or selecting a 3D lidar module.
Source: IDTechEx

Lidar Sensor 핵심 기술 조합



Lidar technology choices. Source: IDTechEx

Lidar Sensor 핵심 기술(1) – 거리 측정 방식

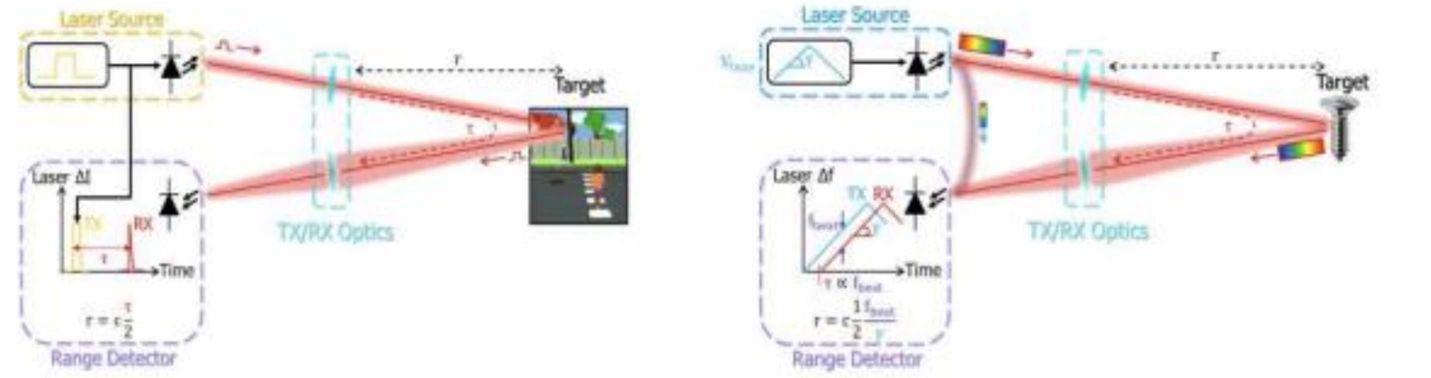


Lidar technology choices. Source: IDTechEx

Lidar Sensor 핵심 기술(1) – 거리 측정 방식

- **Time of Flight**
  - 대다수의 Lidar Sensor들은 ToF 방식을 사용
  - 레이저 광선을 쏘아 물체에서 반사되어 오는 반사광의 걸리는 시간을 측정하여, 물체의 거리 감지
- **Frequency Modulated Continuous Wave (FMCW)**
  - 연속적으로 변하는 연속파 방식의 주파수 변조 레이저 광으로 되돌아온 신호의 위상과 주파수로 거리와 속도를 측정
  - 연속적인 빛의 흐름을 통해 더 먼 거리를 측정할 수 있고, 악천후와 태양광 간섭에 강인하지만, 크기와 비용이 단점

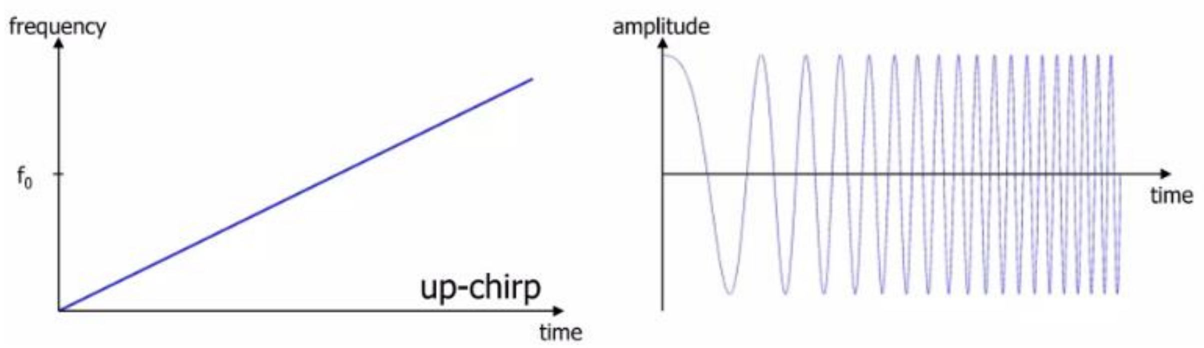
[그림 9] Pulsed TOF 방식(좌)과 FMCW 방식(우)의 비교

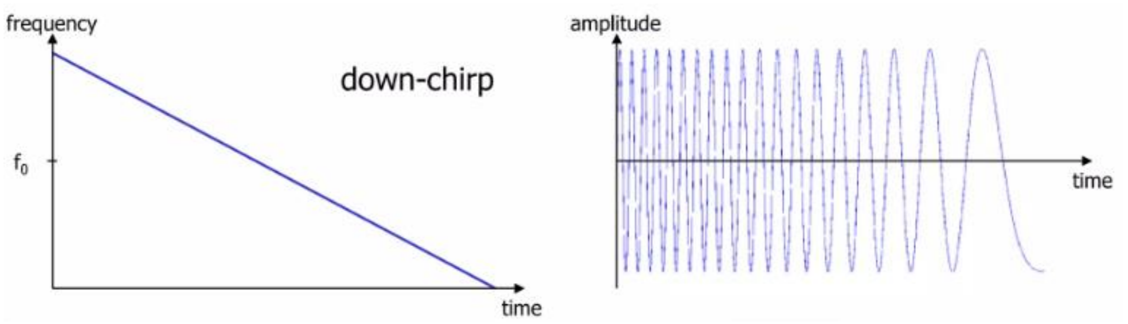


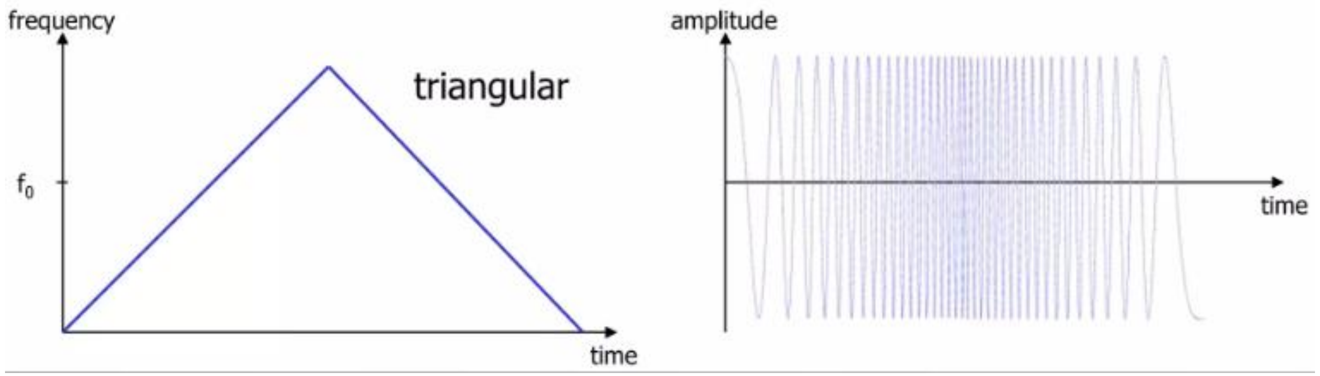
*출처: Philip Sandborn, FMCW Lidar(2019)

Lidar Sensor 핵심 기술(1) – 거리 측정 방식

- **Frequency Modulated Continuous Wave (FMCW)**



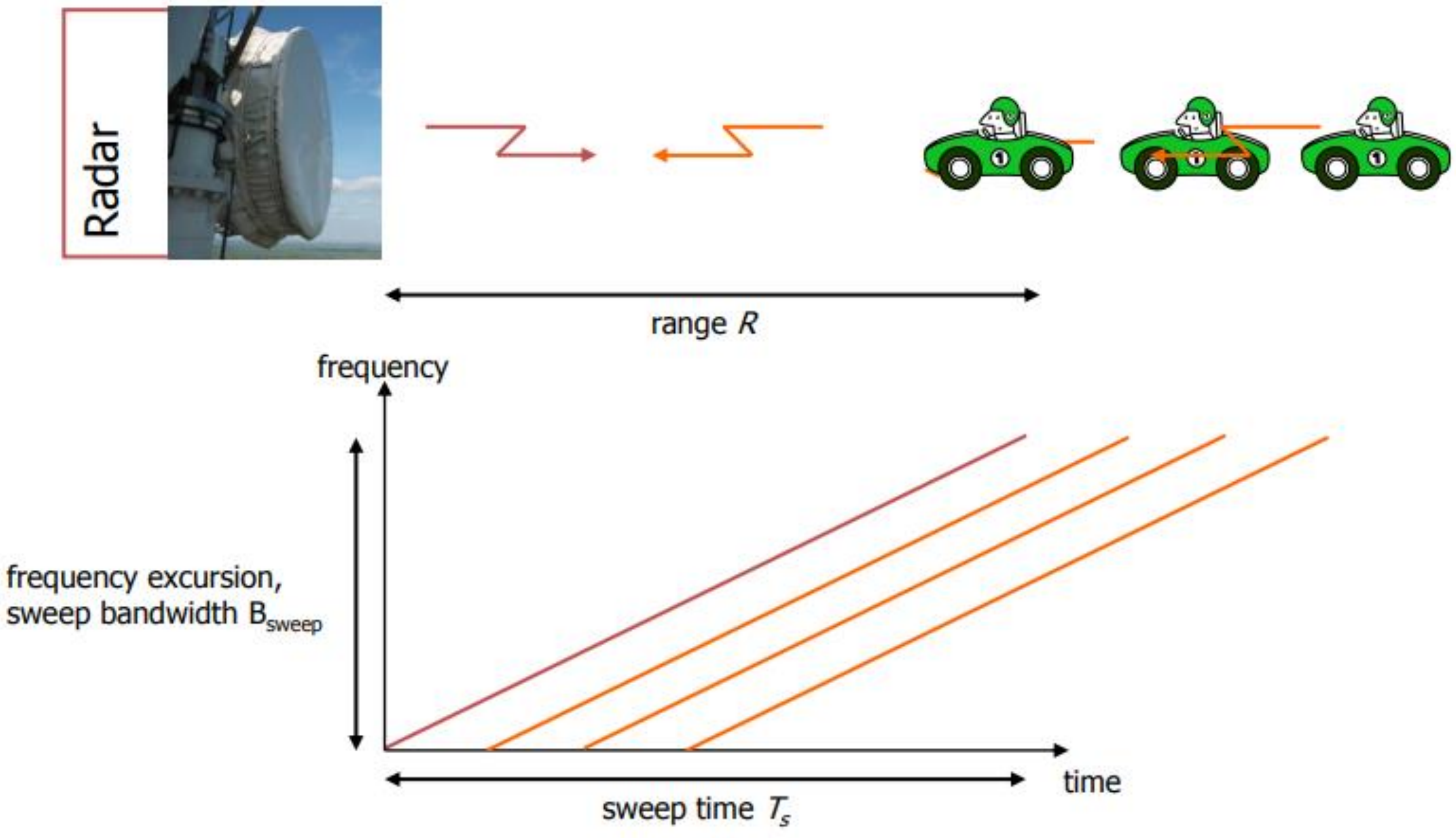




[Ref] https://www.slideshare.net/tobiasotto/principle-of-fmcw-radars

Lidar Sensor 핵심 기술(1) – 거리 측정 방식

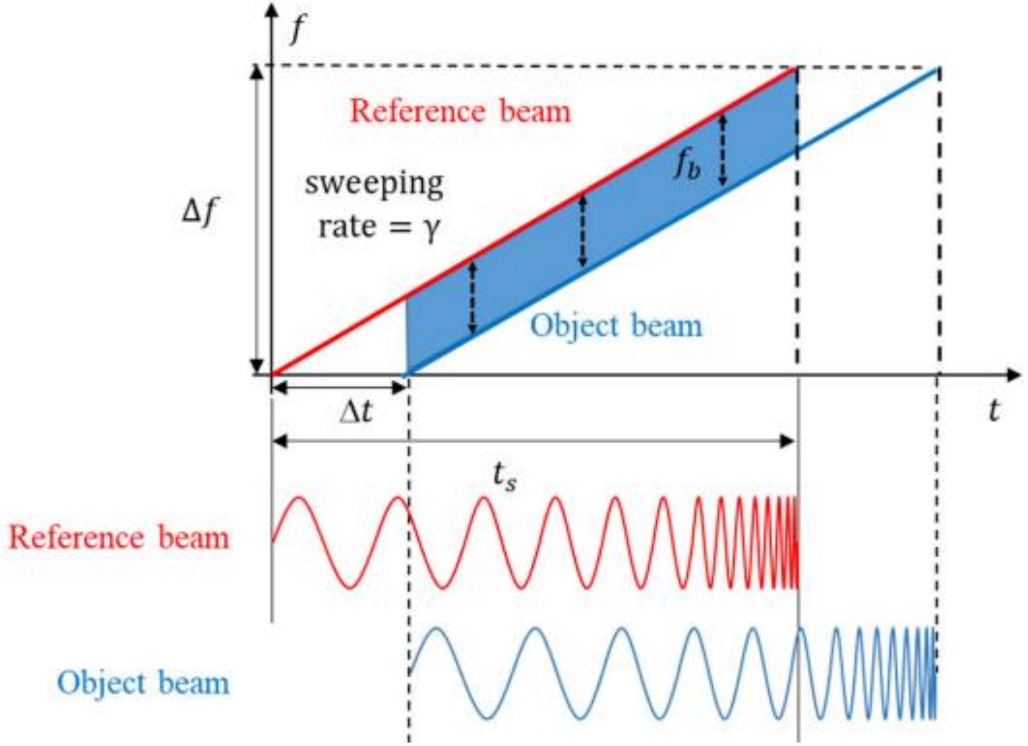
- **Frequency Modulated Continuous Wave (FMCW)**



[Ref] https://www.slideshare.net/tobiasotto/principle-of-fmcw-radars

Lidar Sensor 핵심 기술(1) – 거리 측정 방식

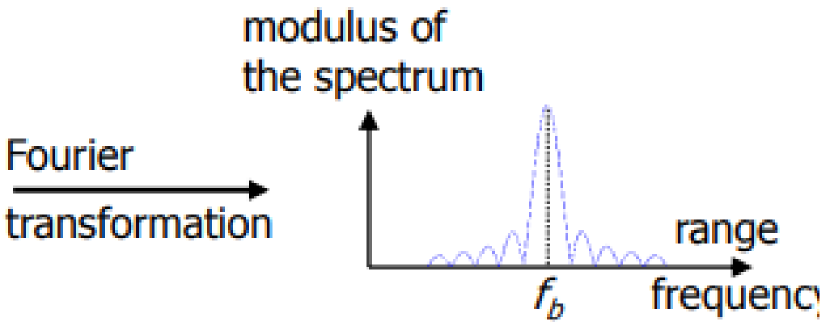
- **Frequency Modulated Continuous Wave (FMCW)**



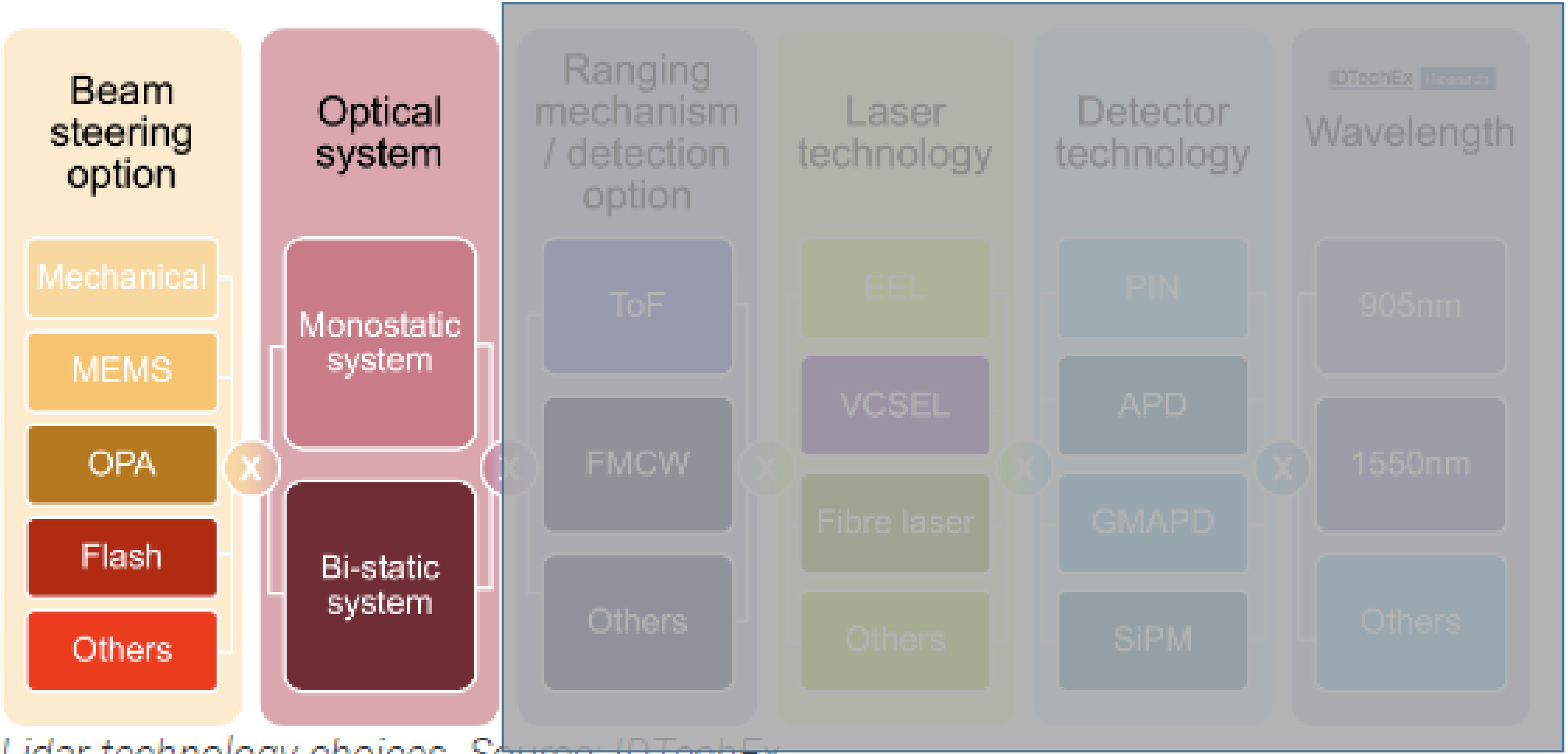
$$d = \frac{c \cdot \Delta t}{2} \qquad \gamma = \frac{\Delta f}{t_s} = \frac{f_b}{\Delta t}$$

f_b : *Beat frequency*
Δf : *sweep bandwidth*
t_s : *sweep time*

$$\boxed{d = \frac{c \cdot \Delta t}{2} = \frac{c \cdot f_b \cdot t_s}{2 \cdot \Delta f}}$$



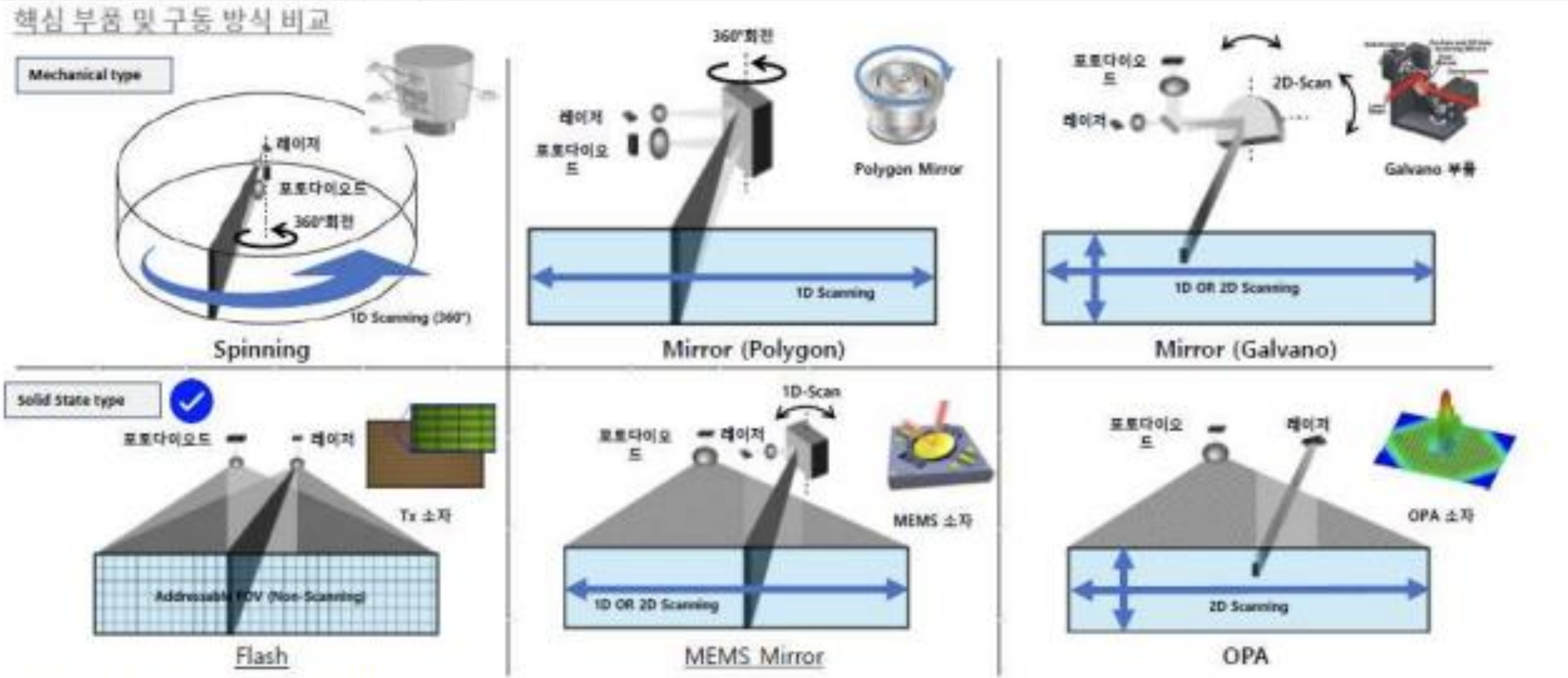
Lidar Sensor 핵심 기술(2) – 레이저 스캐닝 방식



Lidar technology choices. Source: IDTechEx

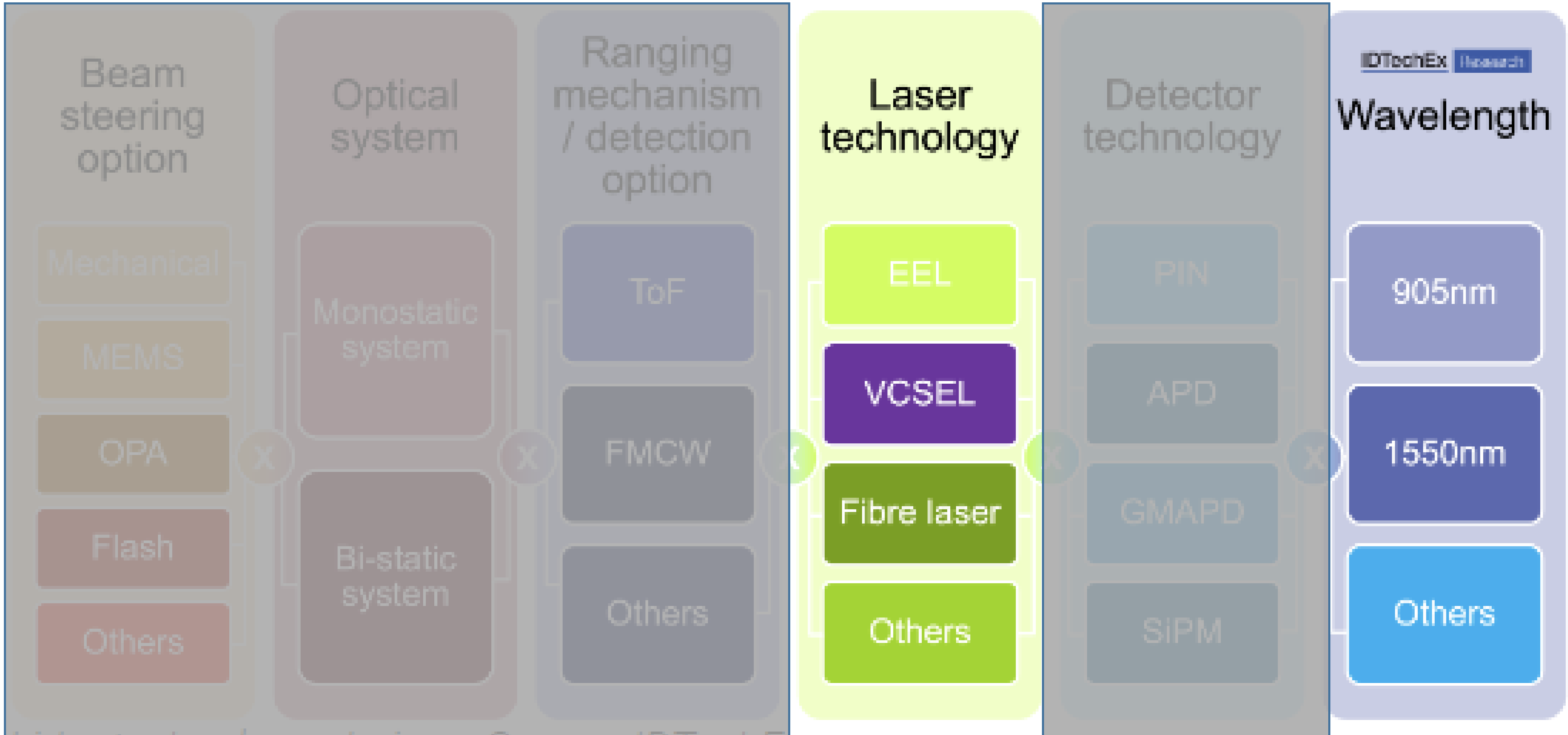
Lidar Sensor 핵심 기술(2) – 레이저 스캐닝 방식

그림51 라이다 핵심 부품 및 구동방식 비교



자료: SOSLAB, 이베스트투자증권 리서치센터

Lidar Sensor 핵심 기술(3) – 레이저 기술

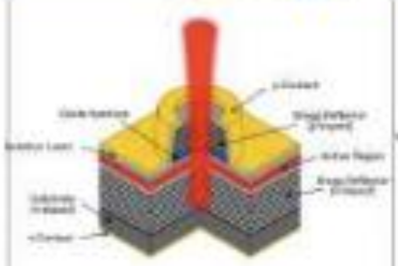
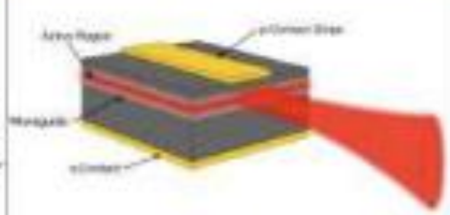


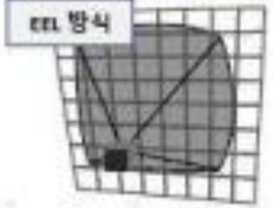
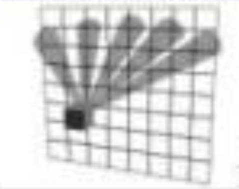
Lidar technology choices. Source: IDTechEx

Lidar Sensor 핵심 기술(3) – 레이저 기술

- **Laser Technology**
  - VCSEL은 파장이 안정적이고 우수한 성능을 제공하며, 최근에는 스마트폰 등 다양한 제품에 탑재되어, 향후 성장세가 확대될 것

그림65 **핵심 송신 소자**

항목	*VCSEL	*EEL
형상		
출력파워 (변환 효율)	30 ~ 55%	50 ~ 60%
출력 집중도 (분산)	중앙 집중 (효율↑)	Gaussian 분포 (효율↓)
온도 특성1 (파장 변화)	0.07 nm/k	0.22 nm/k
온도 특성2 (출력 변화)	-0.05 meV/K	-0.03 meV/K
가격	유사	유사
Array 개수	가능(>10k)	제약 (<16)

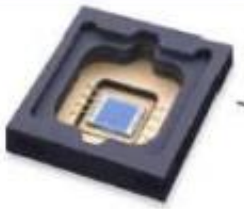
Flash 라이다 방식	장/단점 비교
EEL 방식 	광학계 구성 난이도↑ (EEL 발산각↑) 수신 효율 저하 (수신 Array Gap 영향)
VCSEL 방식 	광학계 구성 및 수신 효율↑ 수신 회로 복잡도 및 출력 데이터량↑
Addressable VCSEL 방식 	광학계 구성 송/수신 효율↑ 수신 회로 복잡도 및 출력 데이터량↓

자료: 각 업체, SOSLAB, 이베스트투자증권 리서치센터

Lidar Sensor 핵심 기술(3) – 레이저 기술

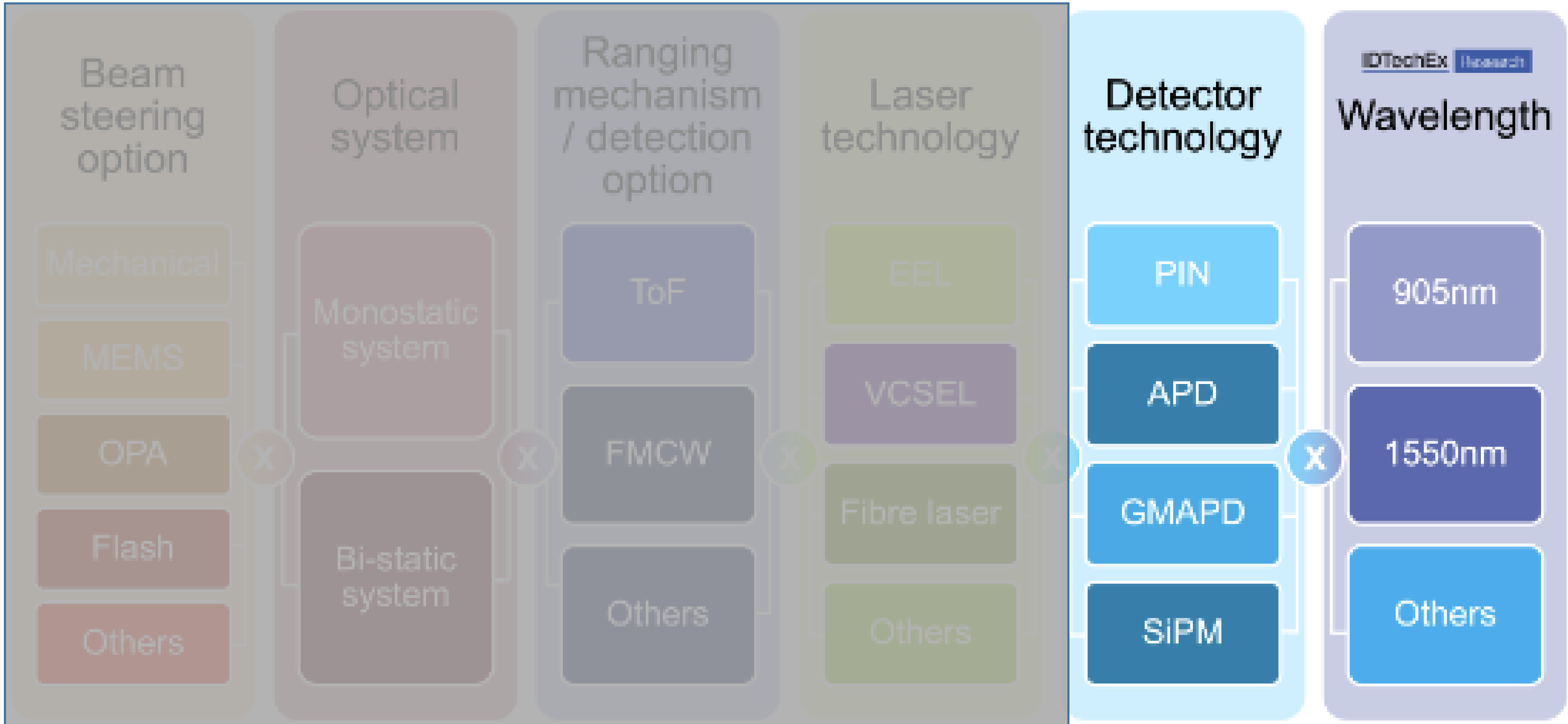
- **WaveLength**
  - Lidar Sensor 파장 대역은 주로 905nm, 1,550nm
  - 905nm는 상대적으로 인식범위가 좁지만, 소모전력이 낮고 수분 흡수력이 낮다
  - 사이즈도 작아 제품화에 유리하고, 비용에서도 우세

그림67 라이다용 레이저 파장 대역

항목	905 nm (830~940)	1,550 nm
레이저 형상	 *Source: II-VI(Finisar)	 *Source: AeroDiode
구성 부품 Size	소형	대형
최대 출력	제한 (Eye safety ↓)	우세 (Eye safety ↑)
환경 영향성 (수증기, 안개 外)	우세 (출력 효율 ↑)	제한 (출력 효율 ↓)
가격	우세 (Si, CMOS 집적화 유리)	열세 (Si, CMOS 집적화 유리)
신뢰성	우세 (905 nm 레이저 신뢰성 우수)	열세 (1550 nm 레이저 신뢰성 우수)
상용화 소자	다수 (Onsemi, Sony, Osram 外)	제한 (대부분 Customizing)

자료: 각 업체, SOSLAB, 이베스트투자증권 리서치센터

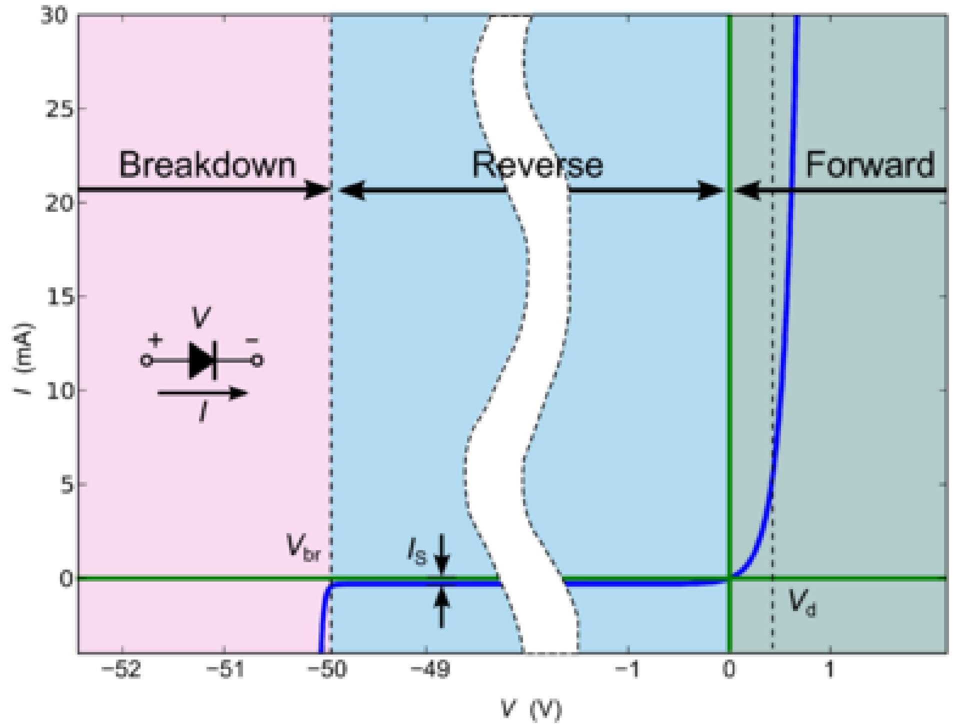
Lidar Sensor 핵심 기술(4) – 디텍터 기술

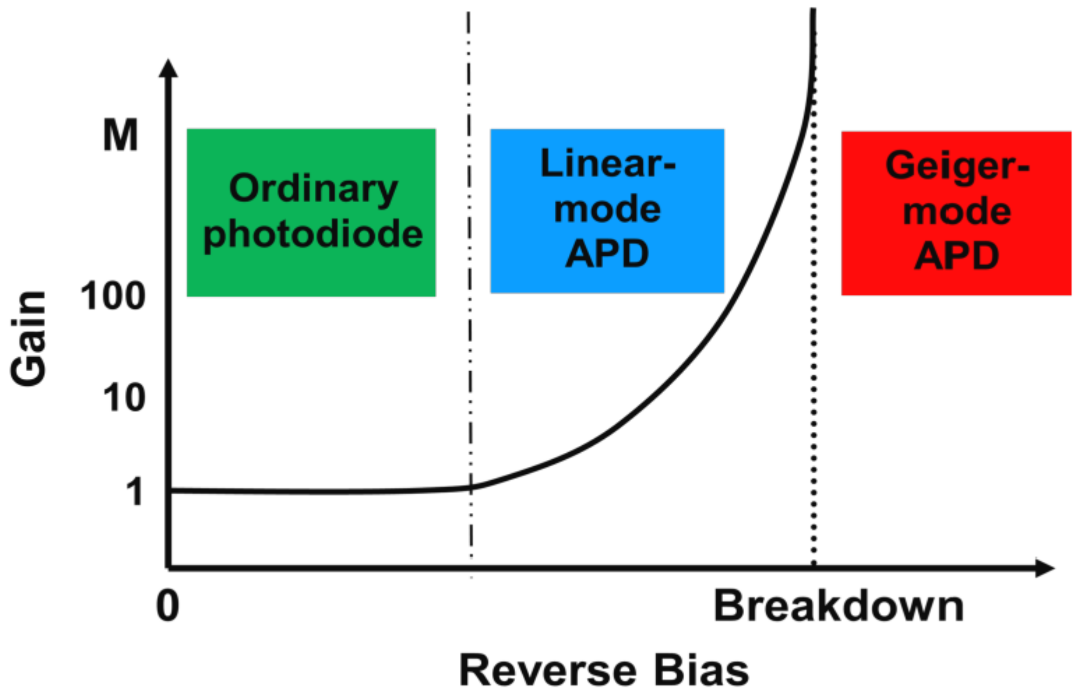


Lidar technology choices. Source: IDTechEx

Lidar Sensor 핵심 기술(4) – 디텍터 기술

- **Diode**
  - 한쪽 방향으로 전류를 흐르게 하는 부품
  - 역방향 전압을 걸어주면 부도체가 되지만, 일정 전압 이상에서 전류가 흐르는 성질이 있음 (Avalanche Breakdown Voltage)





[Ref] https://devocean.sk.com/blog/techBoardDetail.do?ID=164141

Lidar Sensor 핵심 기술(4) – 디텍터 기술

그림66 핵심 수신 소자

항목	*APD	*SPAD	*SIPM
형상	 *Source: First-Sensor	 *Source: On Semiconductor	 *Source: On Semiconductor
수신감도	0.06 kA/W	100 kA/W	100 kA/W
대역폭	<1 GHz	>1 GHz	>1 GHz
온도 특성	1 V/K	21 mV/K	21 mV/K
출력 정보	Intensity + Timing	Intensity + Timing	Intensity + Timing
동작 전압	~ 250V	~ 30V	~ 30V
수신 회로	복잡	간단	보통
노이즈 특성	우세	열세	보통
가격	열세	우세	우세
Array 개수	제약(<128)	가능 (>10k)	제약(<128)

*APD: Avalanche Photo Diode / *SPAD: Single Photo Avalanche Diode / *SIPM: Silicon Photo Multiplier

자료: 각 업체, SOSLAB, 이베스트투자증권 리서치센터

Thank You

3D Sensor Data Processing Curriculum