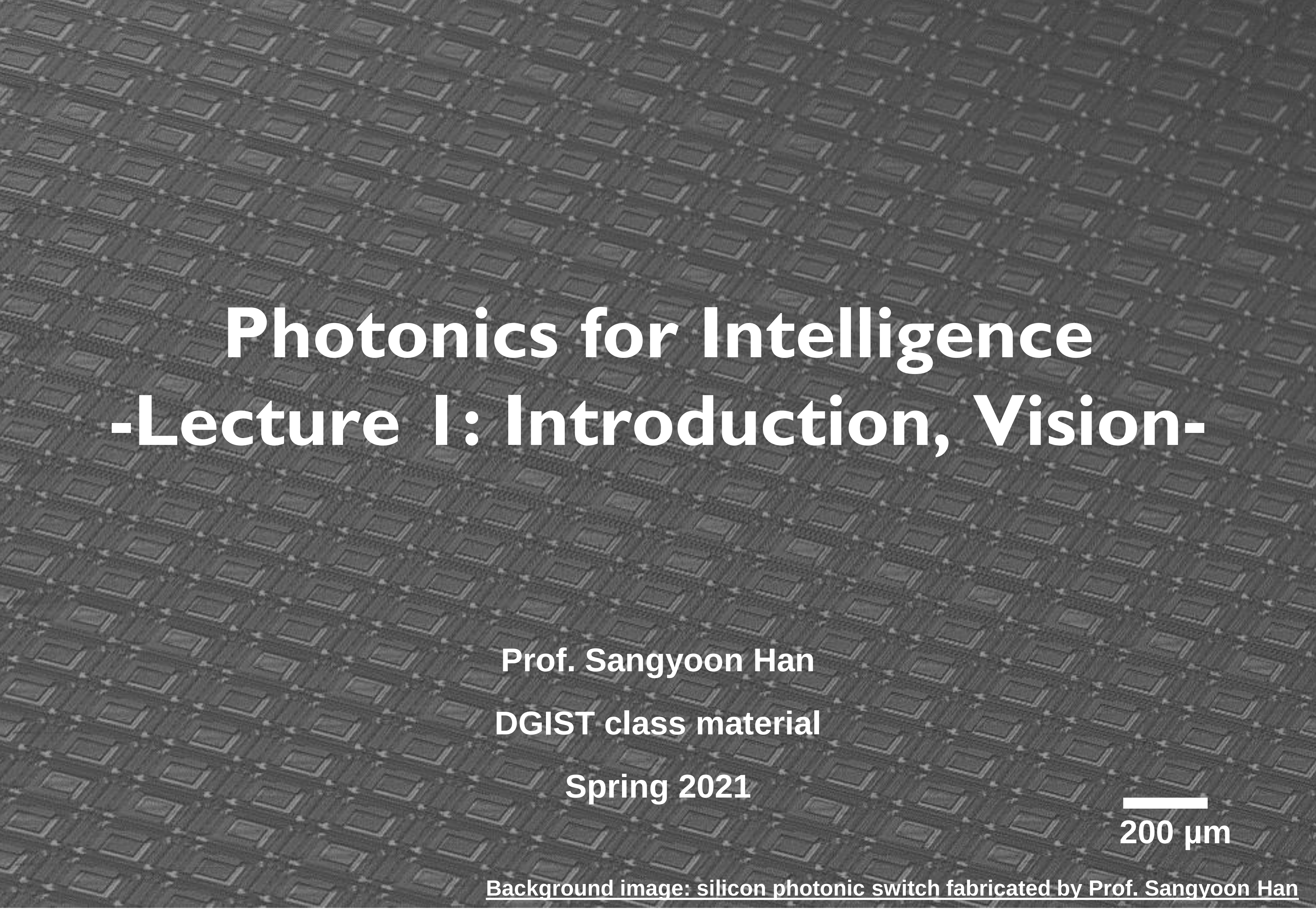
Photonics for Intelligence
-Lecture 1: Introduction, Vision-



Prof. Sangyoon Han

DGIST class material

Spring 2021

Background image: silicon photonic switch fabricated by Prof. Sangyoon Han

Photonics = Study of light

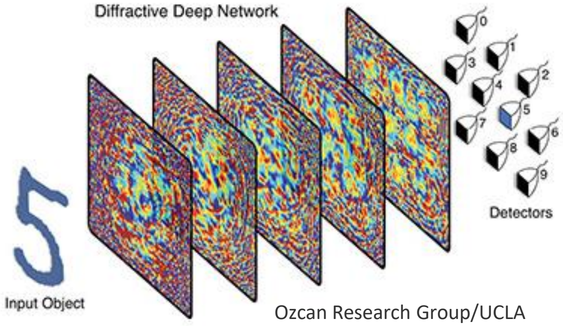
novuslight.com

Photonics = study of light

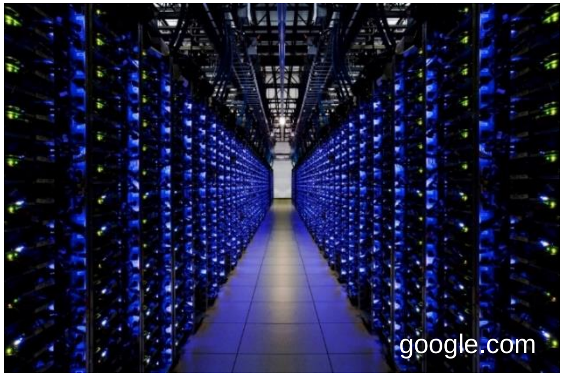
LiDAR

Quantum photonics

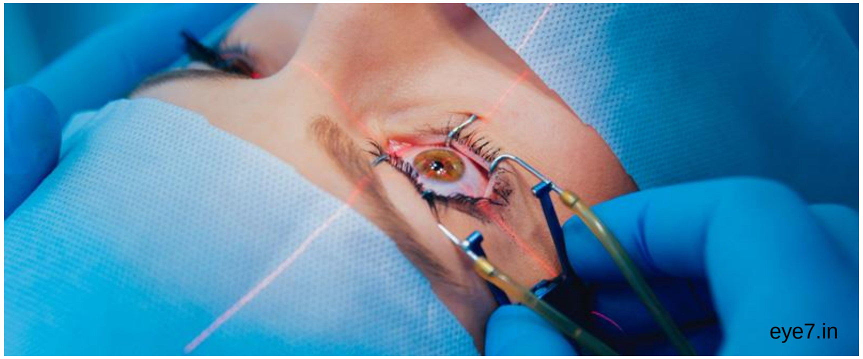
Optical neural net



High-Performance Computing



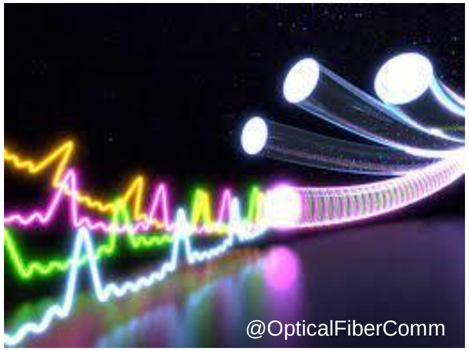
Laser surgery



Spectroscopy

Microscopy

Communications



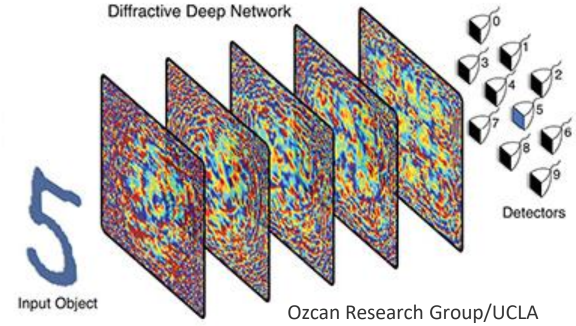
LEDs

Photonics = study of light

LiDAR

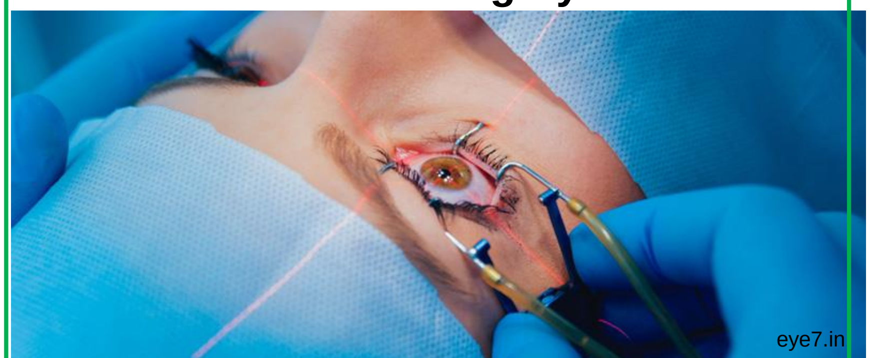
Quantum photonics

Optical neural net



High-Performance Computing

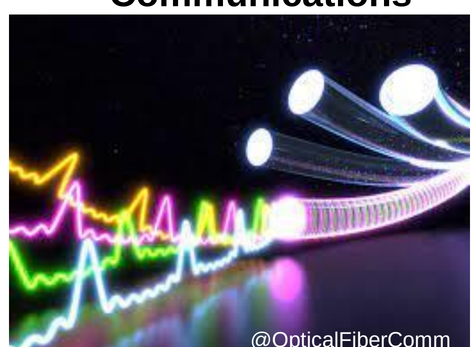
Laser surgery



Spectroscopy

Microscopy

Communications



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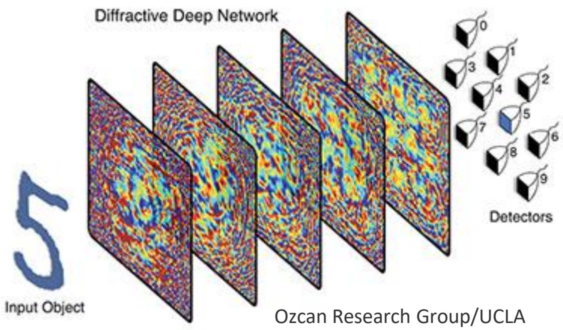
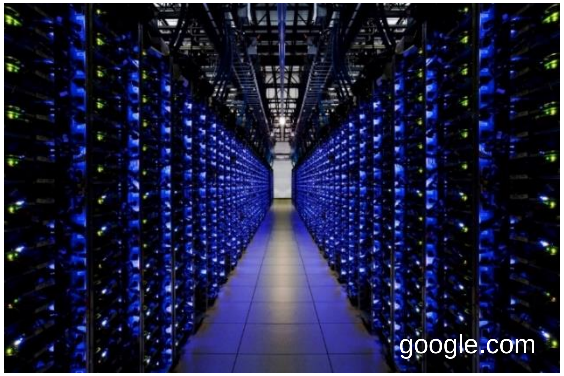
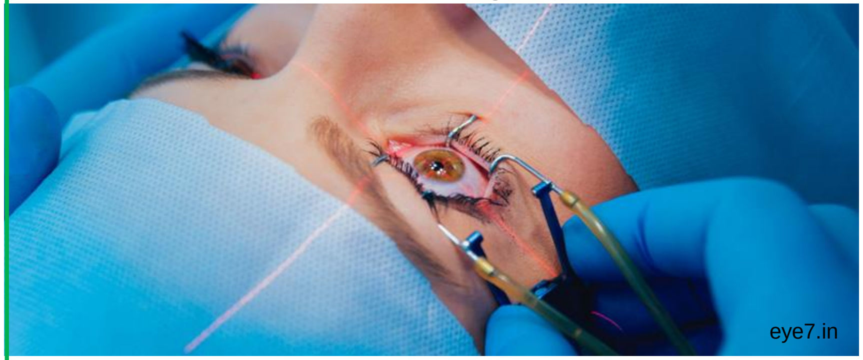


High-Performance Computing



Laser surgery



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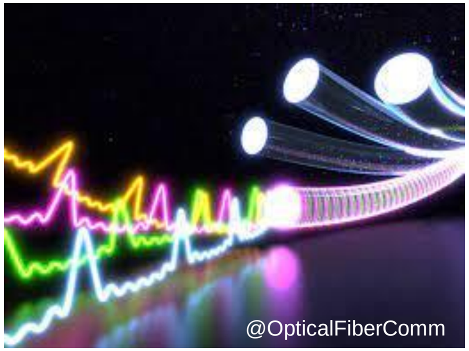

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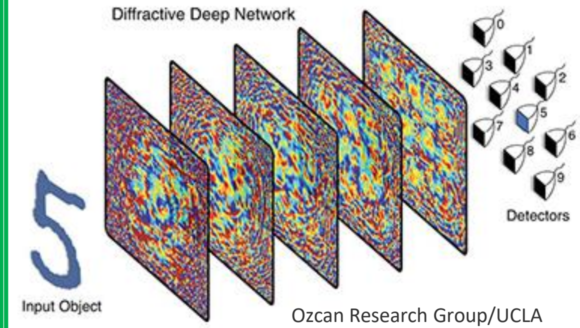
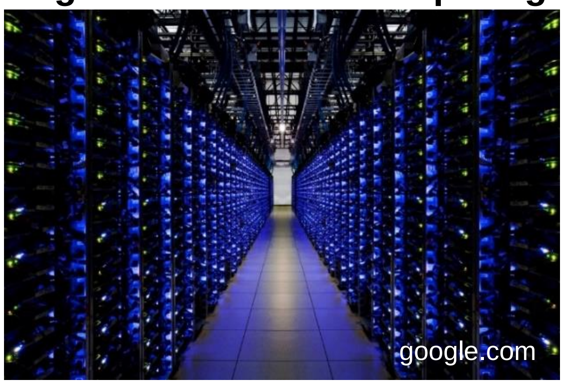


High-Performance Computing



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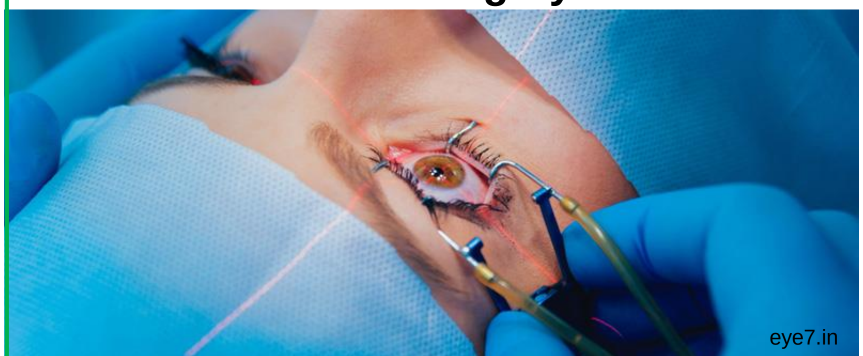


Spectroscopy

Microscopy

Communications

LEDs

Nobel Prizes related to Photonics (~ every 3 years)

- **1902** Physics — **Lorentz and Zeeman** — The Zeeman Effect, Electron Oscillator Model
- **1903** Physiology or Medicine — **Finsen** — Phototherapy – use of UV light to treat Lupus
- **1907** Physics — **Michelson** — The Michelson Interferometer & Precision Measurements
- **1908** Physics — **Lippmann** — Colour Photography based on Interference
- **1911** Physiology or Medicine — **Gullstrand** — Description of the Refractive Optics of the Eye
- **1912** Physics — **Dalén** — Solar-based regulator for buoys and lighthouses
- **1918** Physics — **Planck** — Energy Quanta
- **1919** Physics — **Stark** — The Stark Effect
- **1921** Physics — **Einstein** — Photoelectric Effect & services to theoretical physics
- **1922** Physics — **Bohr** — Atomic Structure and the nature of radiation
- **1923** Physics — **Millikan** — Elementary Charge and the Photoelectric Effect
- **1927** Physics — **Compton** — The Compton Effect
- **1930** Physics — **Raman** — Raman scattering
- **1932** Physics — **Heisenberg** — Creation of Quantum Mechanics
- **1933** Physics — **Schrodinger and Dirac** — New Productive Forms of Atomic Theory
- **1945** Physics — **Pauli** — Pauli Exclusion Principle
- **1953** Physics — **Zernike** — Phase Contrast Microscope
- **1954** Physics — **Born** — Statistical Interpretation of the Wavefunction
- **1955** Physics — **Lamb** — Fine structure of the H Spectrum (Lamb Shift, QED)
- **1964** Physics — **Townes, Basov, and Prokhorov** — Maser-Laser Principle
- **1966** Physics — **Kastler** — Precision studies of optical resonances
- **1967** Physiology or Medicine — **Granit, Hartline, and Wald** — Physiological and chemical visual processes in the eye
- **1967** Chemistry — **Eigen, Norrish, and Porter** — Flashlamp Pump-Probe Studies of Chemical Reactions (μs)
- **1971** Physics — **Gabor** — Holography
- **1981** Physics — **Bloembergen and Schawlow** — Laser Spectroscopy
- **1981** Physiology and Medicine — **Hubel and Wiesel** — Information Processing in the Visual System
- **1989** Physics — **Ramsey, Dehmelt, and Paul** — Atomic Clocks, the Ion Trap
- **1997** Physics — **Chu, Cohen-Tannoudji, and Phillips** — Laser Cooling and Trapping
- **1999** Chemistry — **Zewail** — Femtochemistry
- **2000** Physics — **Alferov and Kroemer** — Optoelectronics, Semiconductor Heterostructures
- **2001** Physics — **Cornell, Ketterle, and Wieman** — Bose Einstein Condensation
- **2005** Physics — **Glauber, Hall, and Haensch** — Quantum Optics, Spectroscopy, Optical Frequency Comb
- **2008** Chemistry — **Shimomura, Chalfie, and Tsien** — Green Fluorescent Protein GFP
- **2009** Physics — **Kao, Boyle, and Smith** — Optical Fiber Communications ; Imaging and the CCD
- **2012** Physics — **Haroche and Wineland** — Individual Quantum Systems
- **2014** Physics — **Akasaki, Amano, and Nakamura** — The Blue LED and Energy-Saving White Light Sources
- **2014** Chemistry — **Betzig, Hell, and Moerner** — Super-resolution microscopy
- **2018** Physics — **Ashkin, Mourou, and Strickland** — Optical Tweezers & Biophotonics; Chirped Pulse Amplification

John M. Dudley, "Light, Lasers, and the Nobel Prize," Adv. Photon. 2(5) 050501 (10 October 2020)

What makes photonics (light) so special?

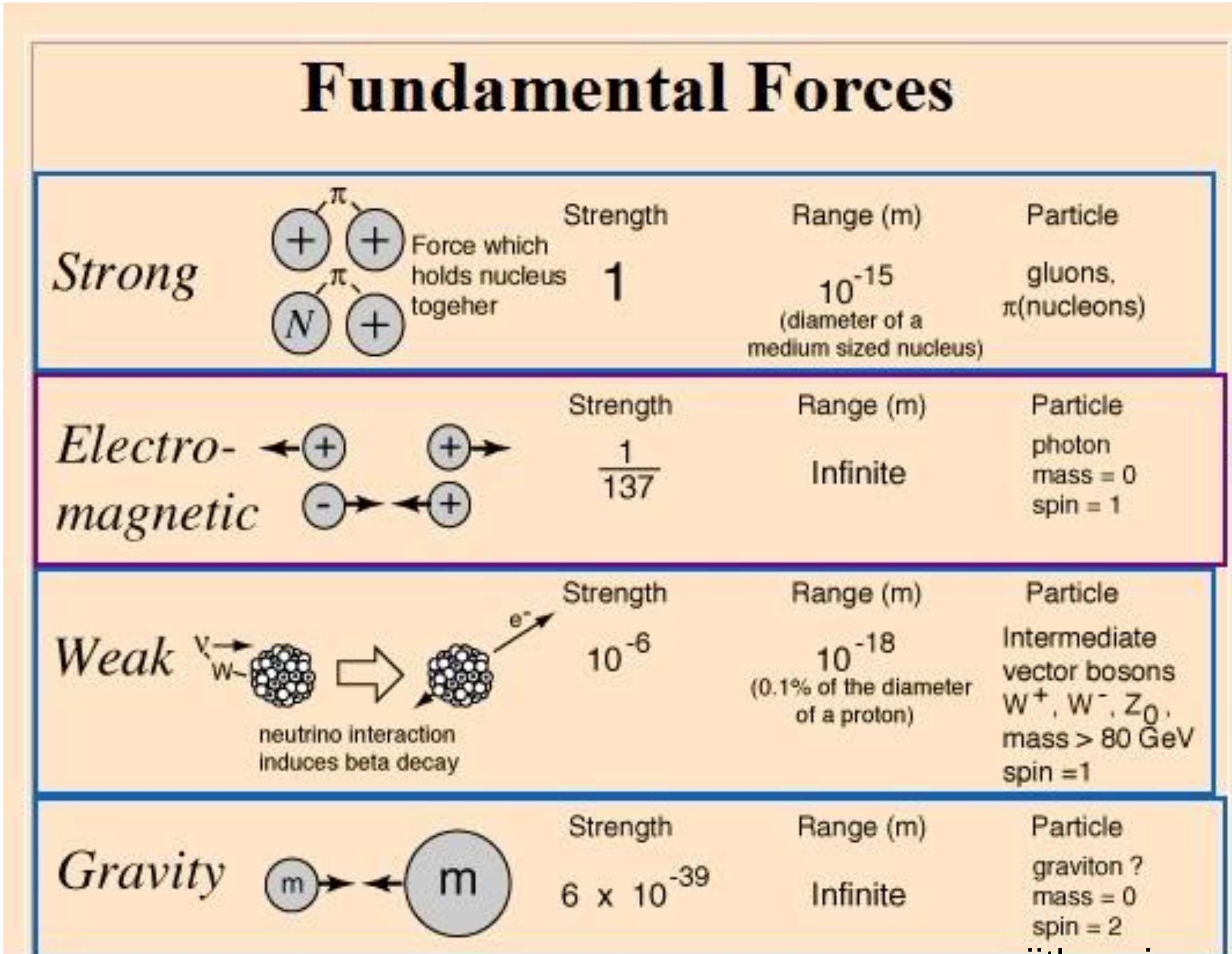
What is light?

novuslight.com

- **Light = wave of electro-magnetic field**
  - **Field ∝ force**

- **What are electric field? magnetic field?**

How many forces are in nature?



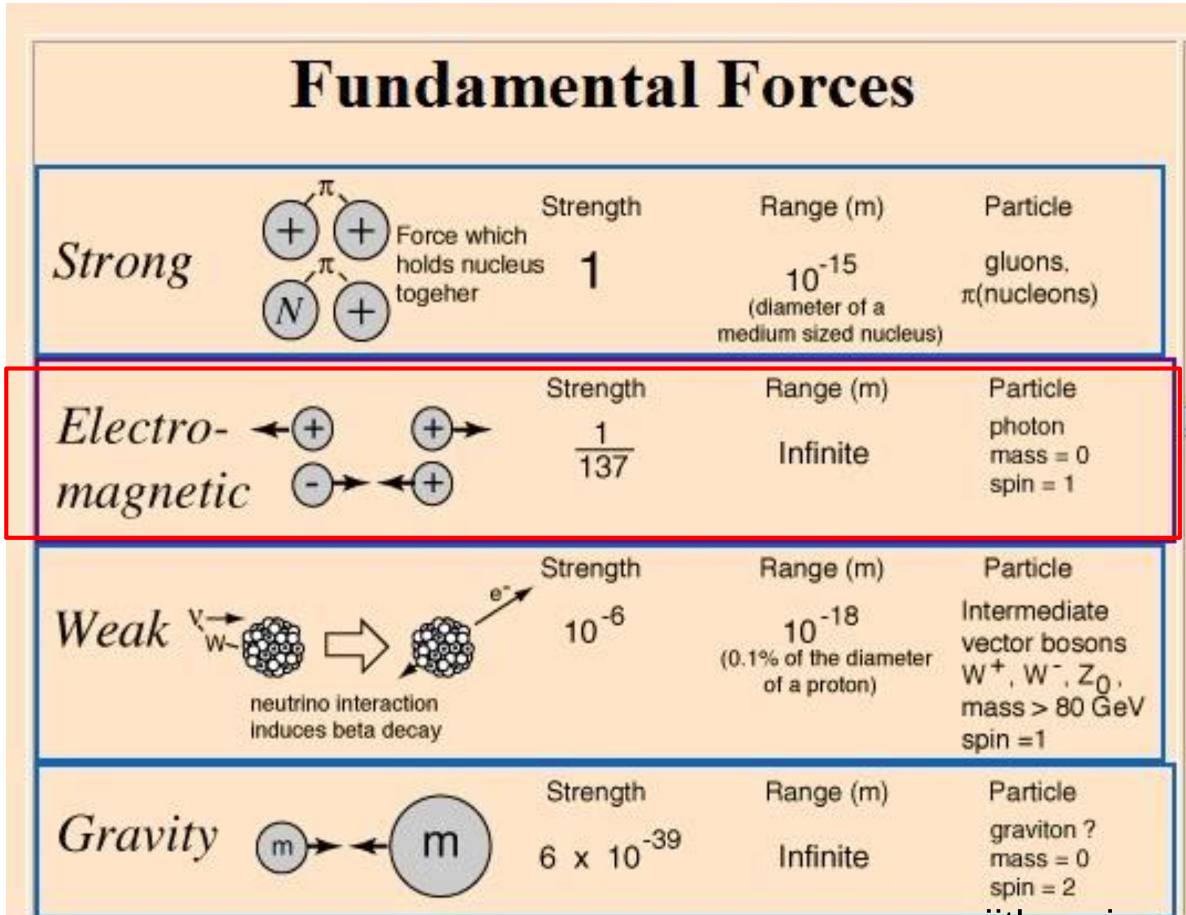
Fundamental Forces

Force	Description	Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

iitk.ac.in

- **Only four, surprise?**

What is the really usable force?



iitk.ac.in

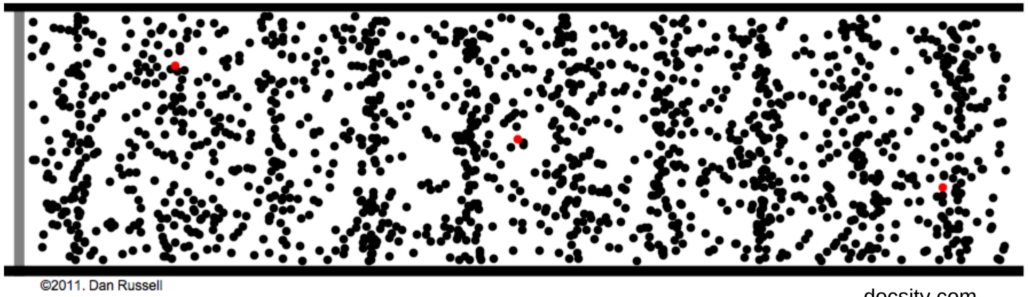
- 없으면 우주 멸망
- 핵무기 및 원자력 발전 만들 수 있다…
- 거리도 적당, 힘도 적당!
- 원자핵 붕괴에 관여하는 힘
- 없으면 문명 붕괴
- 행성 하나 질량 정도는 있어야…

- **Electro-magnetic force is the only tangible force in daily life**
  - **Reasonable strength and range**
- **You can't really play with gravity**

Wave

Poking (direct force)

Sound wave (remote force)

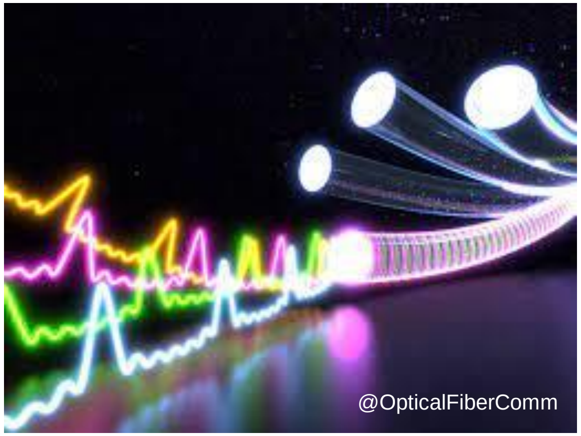


docsity.com

- **Wave allows remote action (e.g. sound wave)**
- **Wave carries energy and information**

Yes, light is electro-magnetic wave

<Optical communications>



Do you know the era of modem? (download 1 image takes 3 mins, year 1999)

<TV>

We watch, not listen

<LiDAR>

Fast & precise measurements

- **Light is very fast: no latency**
  - **$c = 3 \times 10^8$ m/s (cf. speed of sound = 343 m/s)**
- **Light is very high frequency: high bandwidth**
  - **Red light: 4×10^{14} Hz (cf. human voice: 200 Hz)**
- **Period of light (wavelength) is very small: high precision**
  - **Red light: 6×10^{-7} m (cf. sound wave: 2m)**

From camera to LiDAR

Camera (2D vision) VS LiDAR (3D vision)

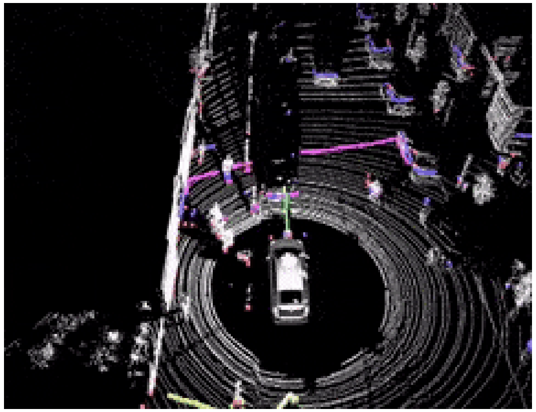
Camera

canon-cna.com

From movie “Good Will Hunting”

LiDAR

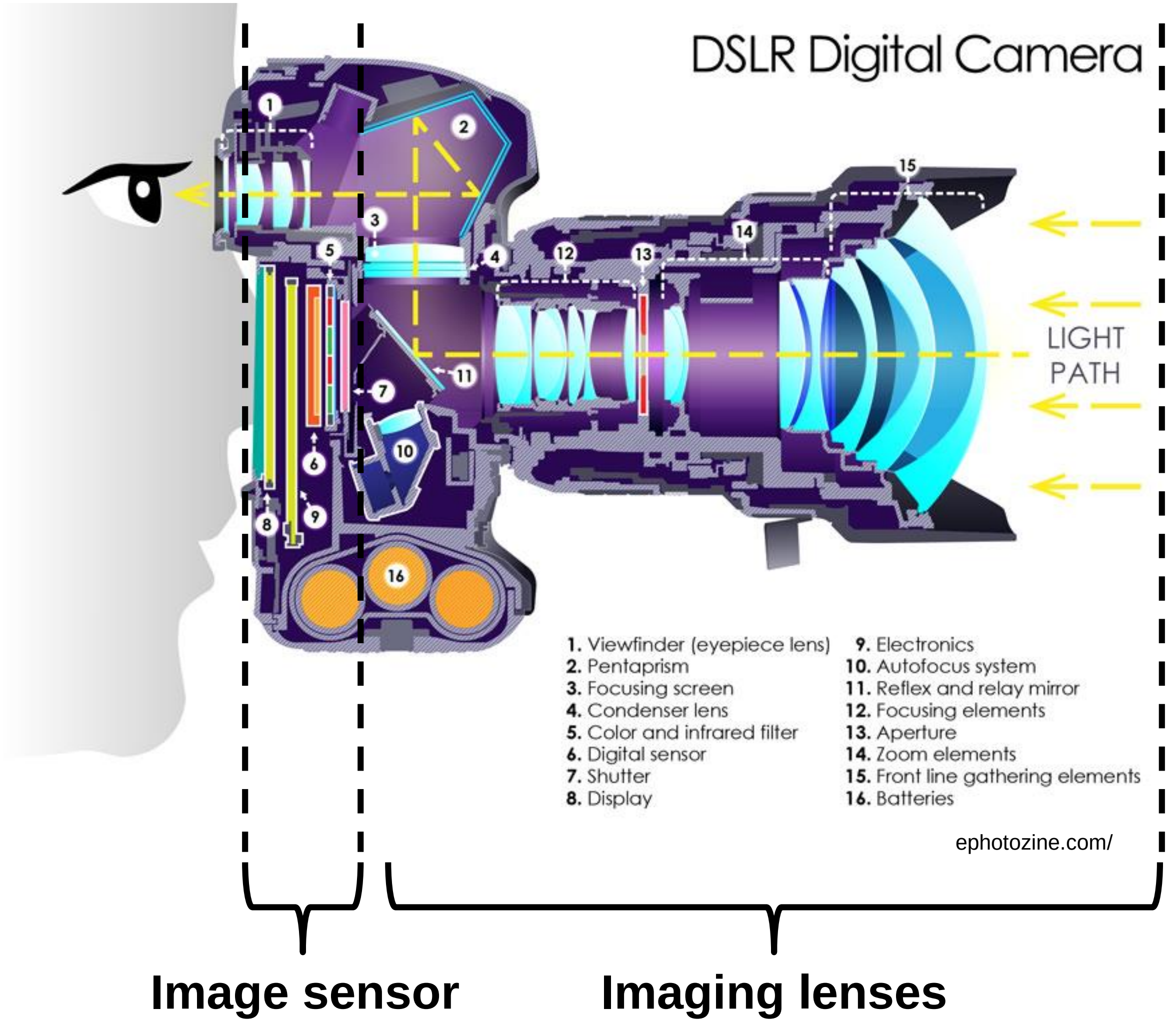
velodynelidar.com



youtube.com/watch?v=nXlqv_k4P8Q

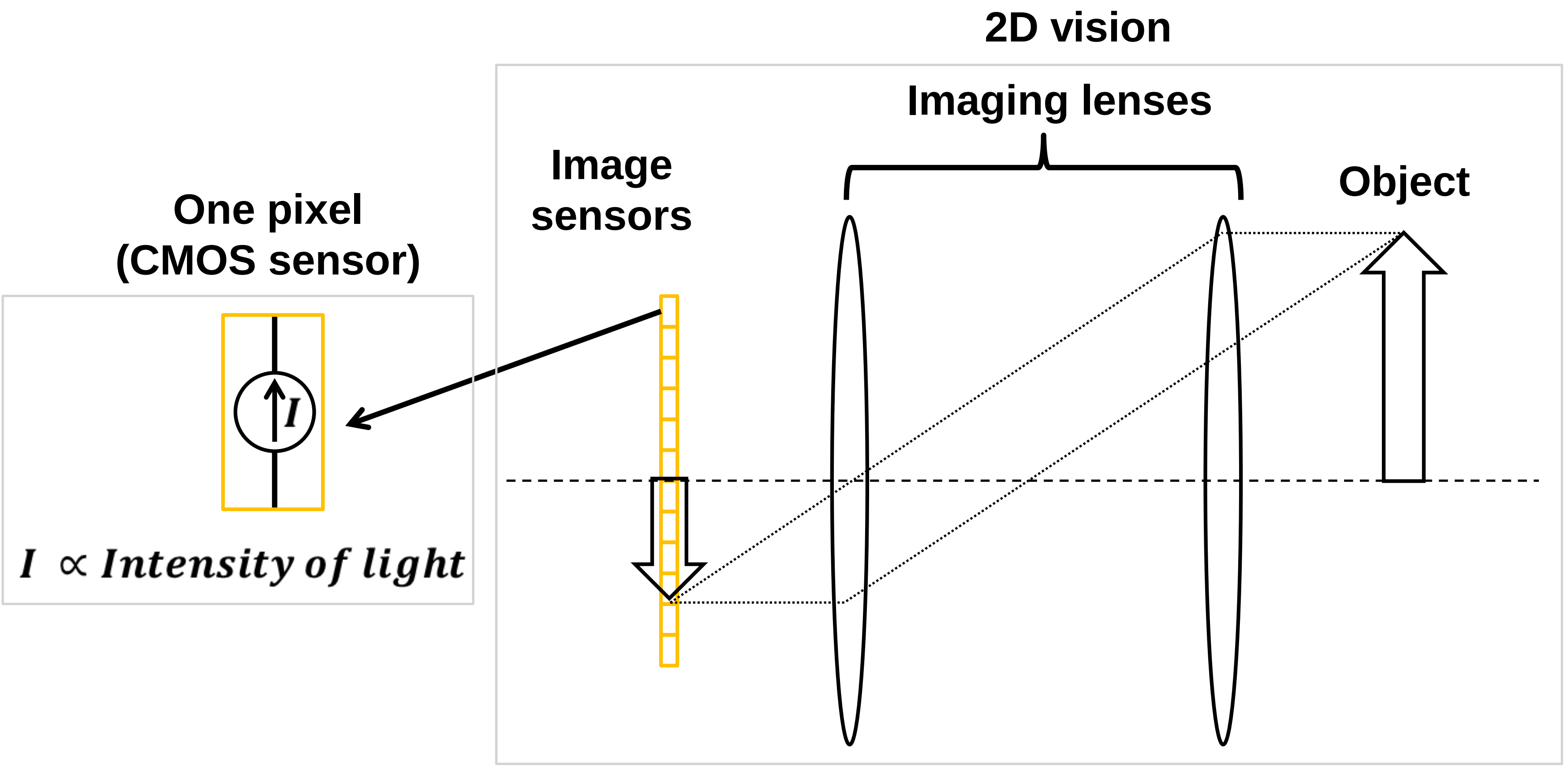
- **LiDAR (3D) = Camera (2D) + distance information (1D)**

Digital camera: how it works?



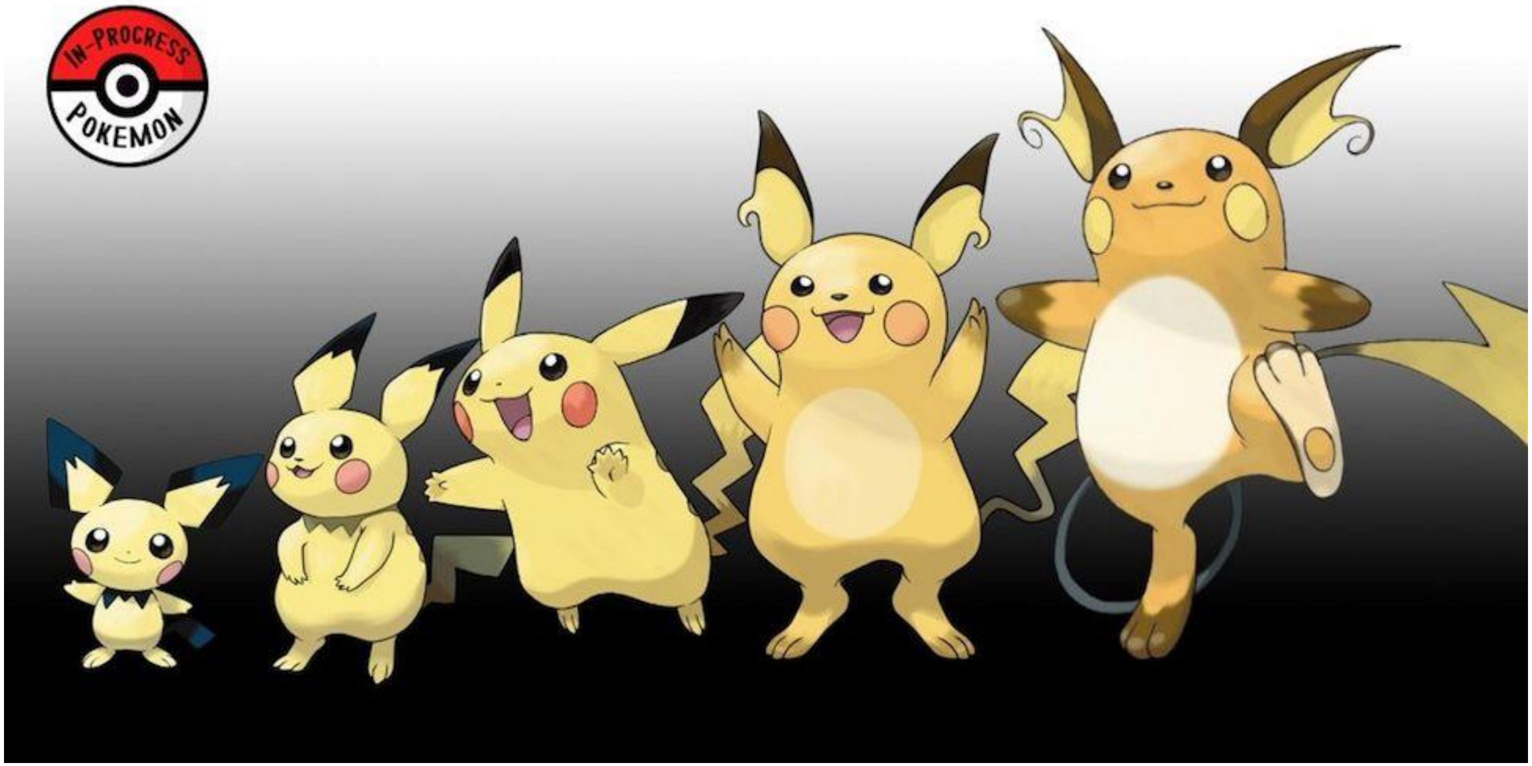
- **Looks complicated, but it is really simple actually**

2D vision



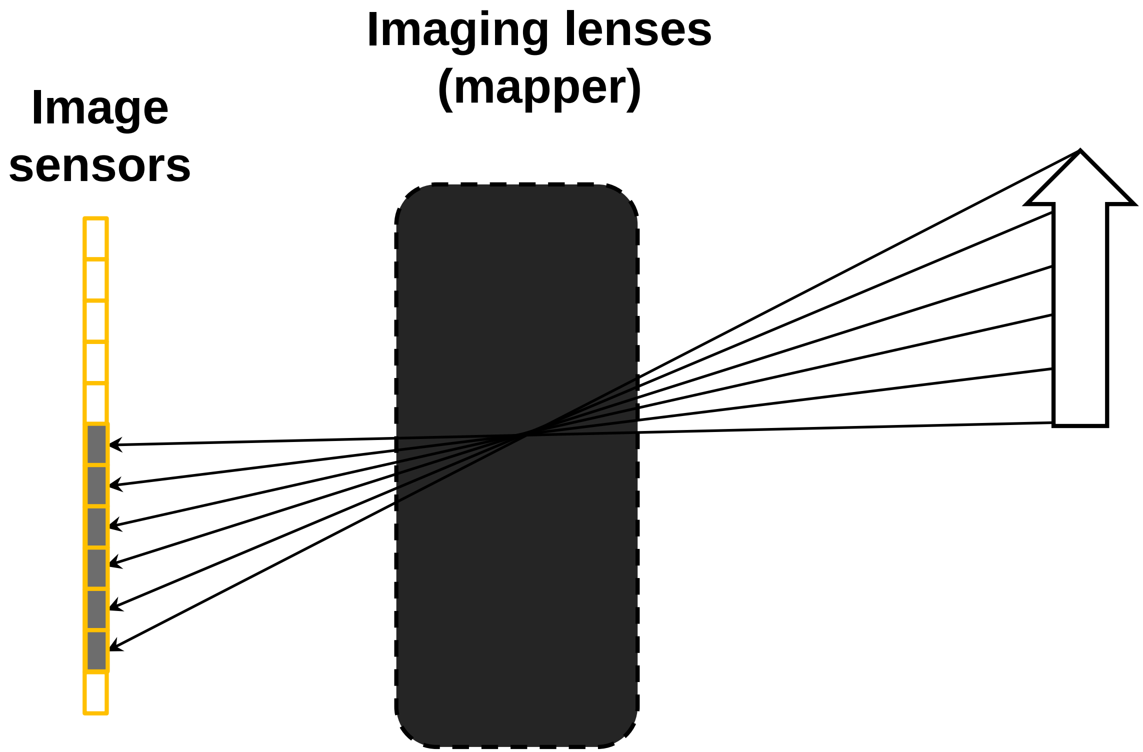
- **2D vision (camera) is as simple as this**

Let's follow the evolution one by one



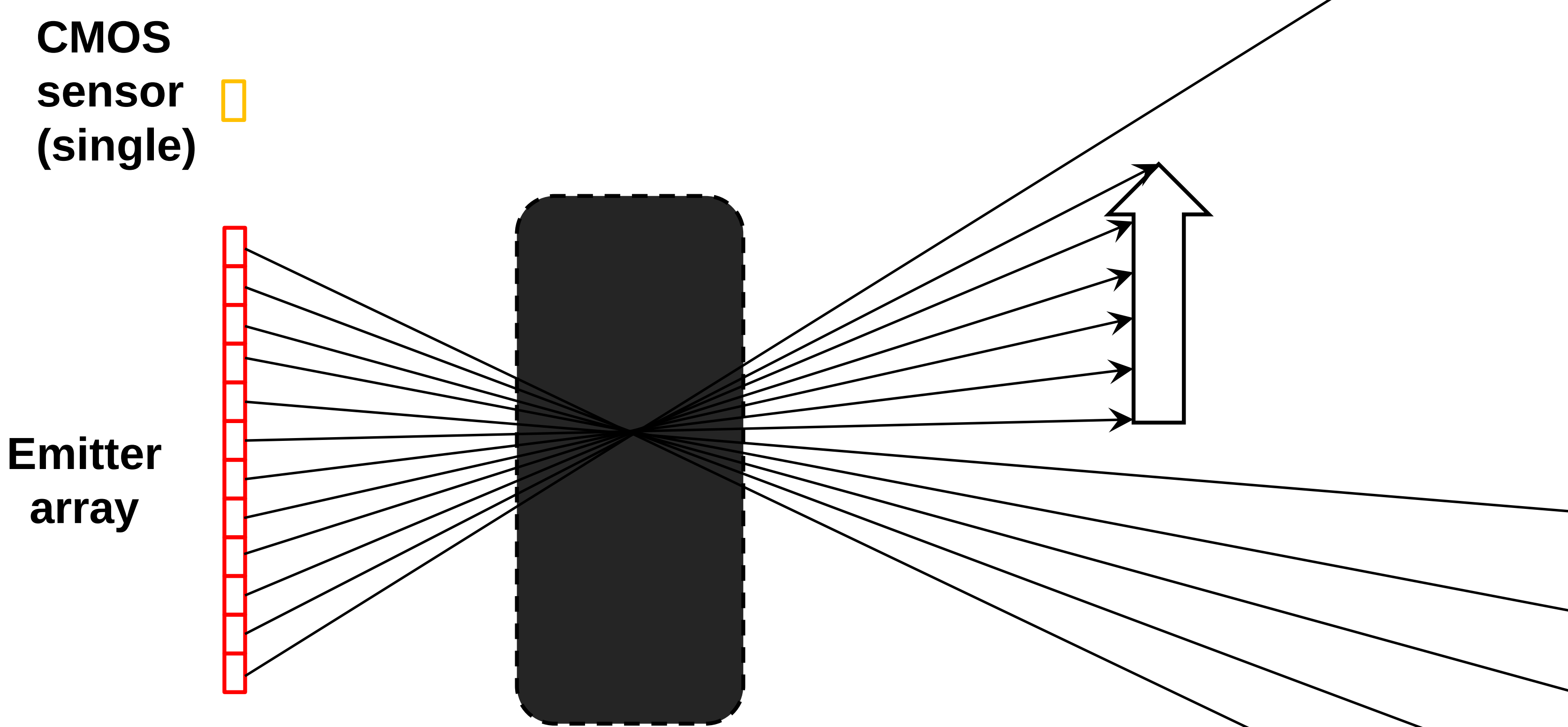
2D vision → 3D vision

2D vision (more simplified)



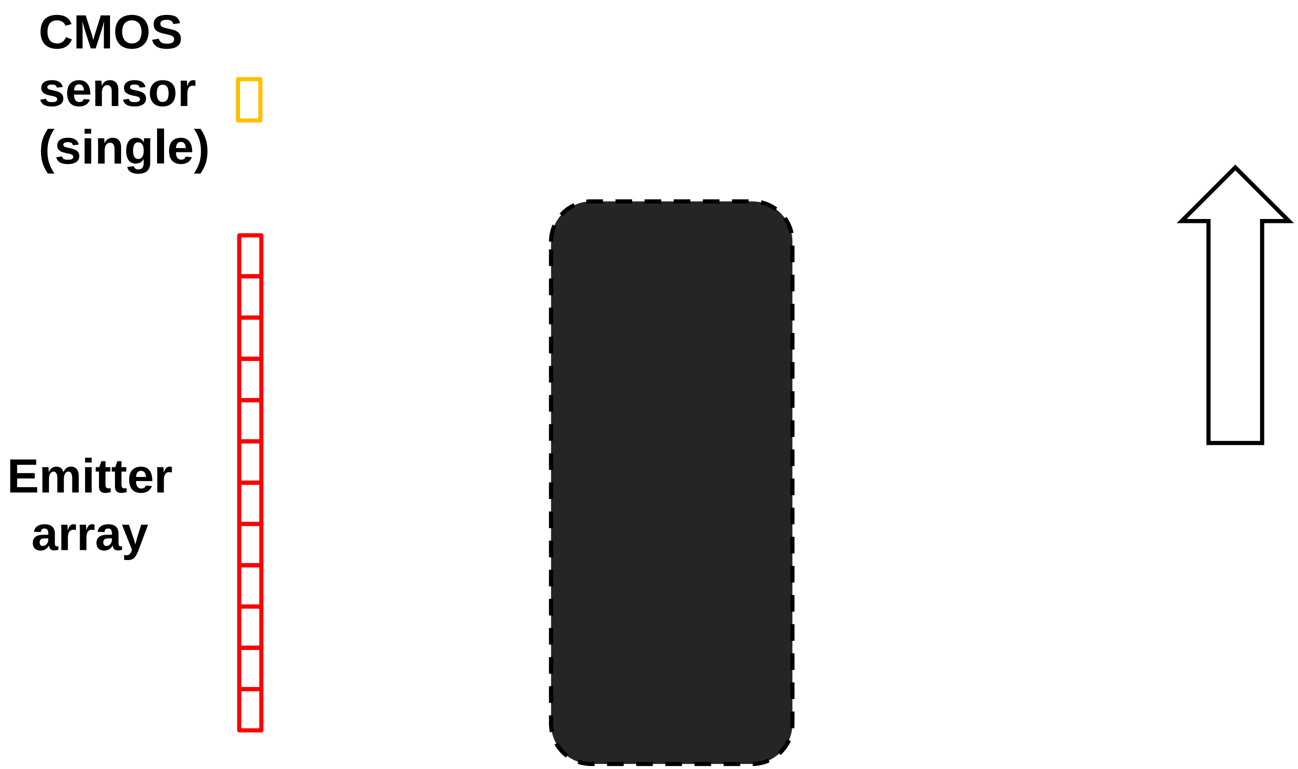
- **Nothing more than sensor & mapper complex**

Tweaked 2D vision (Ver1)



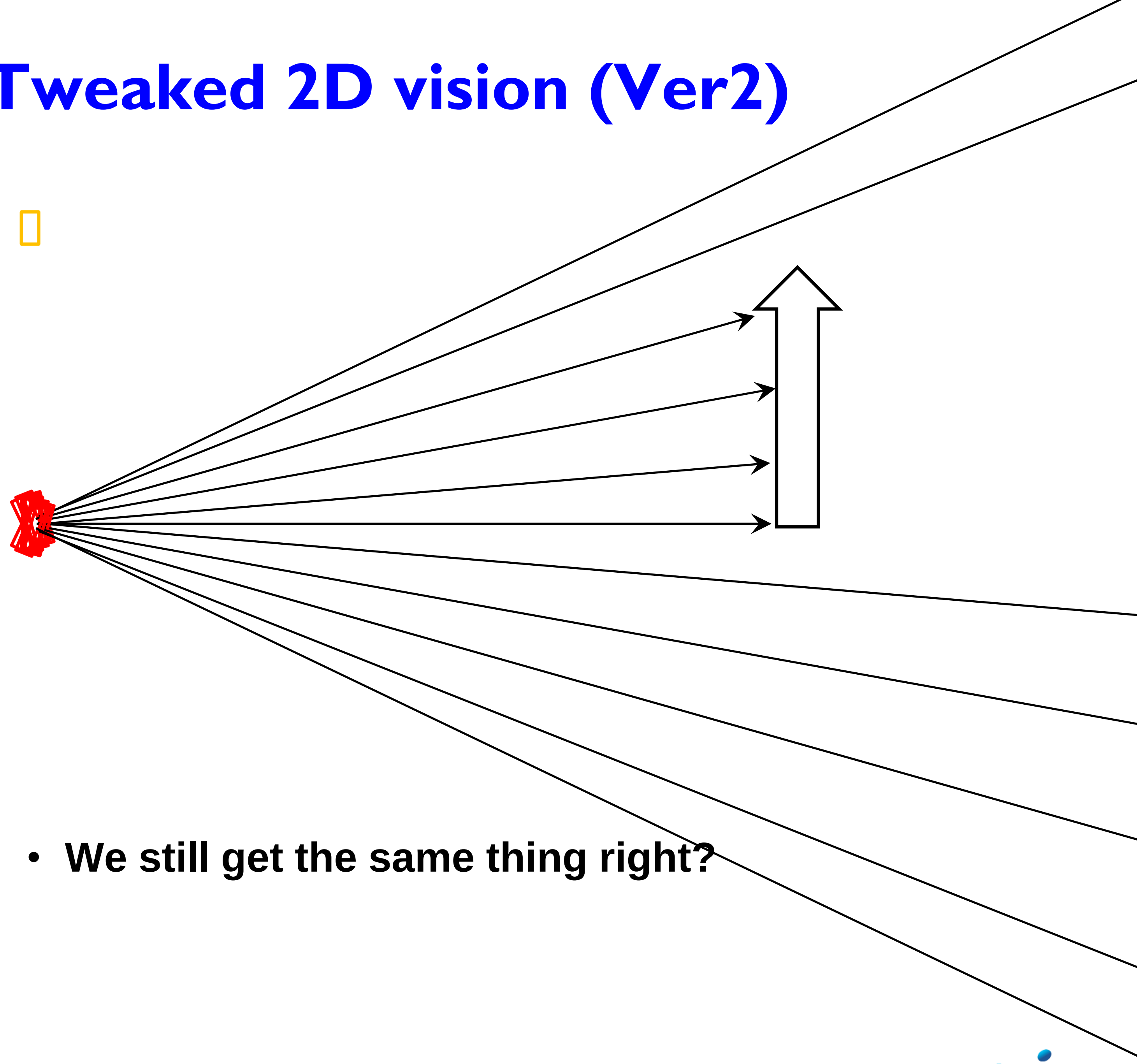
- What if we reverse the direction of light
- Emit light from the pixels (laser or LED)
- Measure the amount of light scattered from the object
- We can still construct the image (can you visualize it in your head?)

Tweaked 2D vision (Ver1)



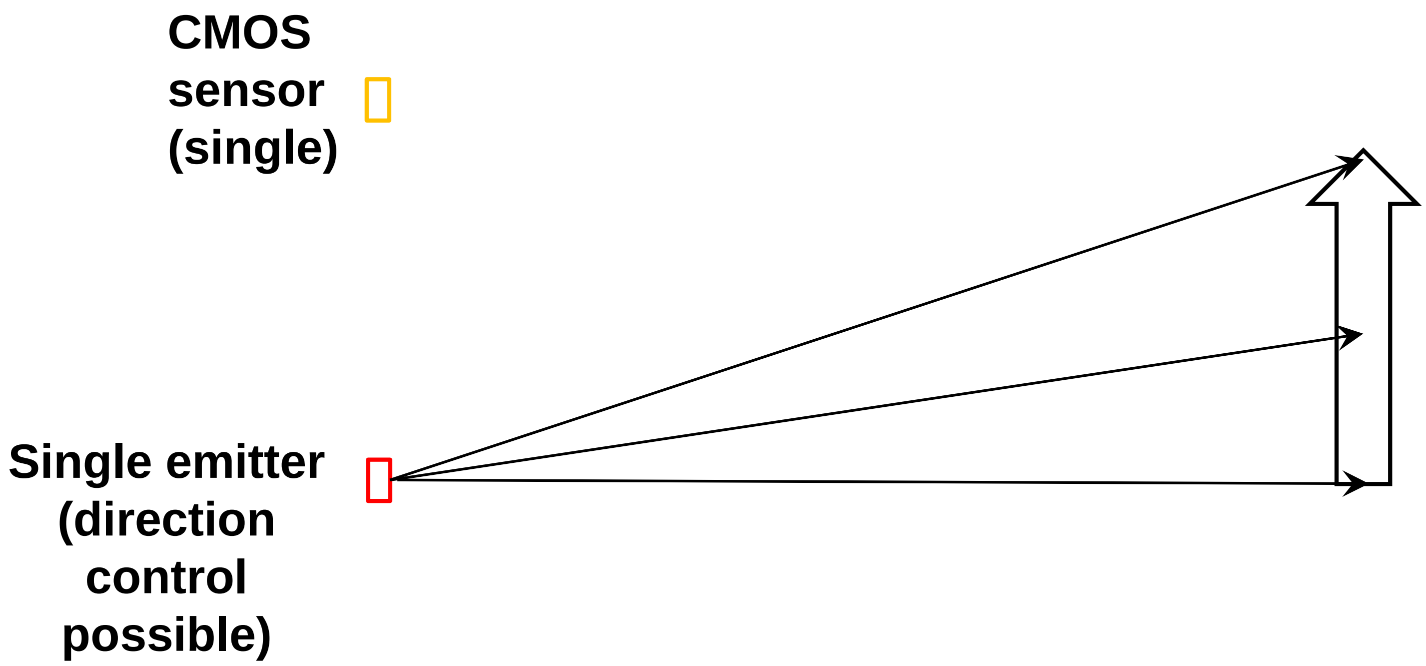
- What if we reverse the direction of light
- Emit light from the pixels (laser or LED)
- Measure the amount of light scattered from the object
- We can still construct the image (can you visualize it in your head?)

Tweaked 2D vision (Ver2)



- **We still get the same thing right?**

3D vision (LiDAR)



- Use pulse to measure the distance
- Measure the time-of-flight (ToF)

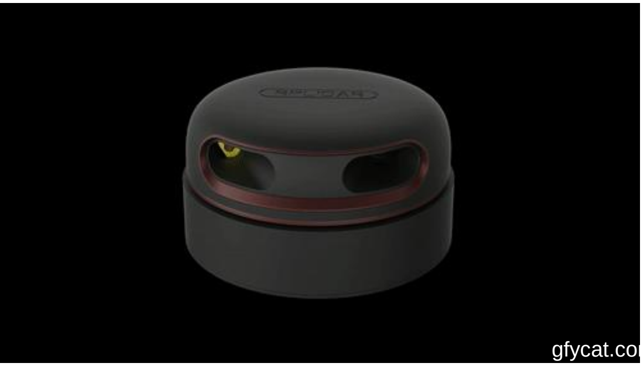
What are the important aspects?

ifixit.com

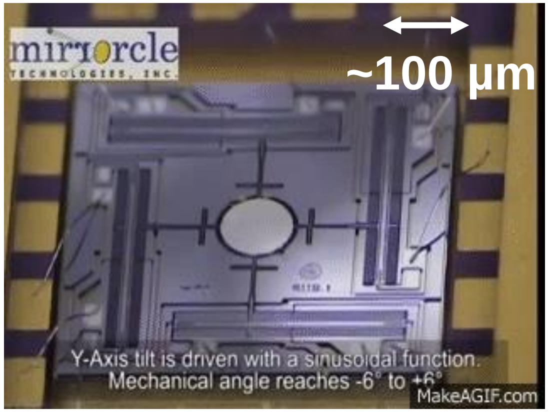
- **Beam scanning**
  - **We need fast scanning speed**
  - $\boldsymbol{Frame\ rate = \frac{1}{N*\tau},\ \ N\text{: \# } of\ pixel,\ \ \tau\text{: time for switching to next pixel}}$
- **Timing**
  - **Light is so fast (e.g. only 33x10^{-9} sec for traveling 10 meters)**
  - $\boldsymbol{\Delta t < \frac{\Delta d}{c},\ \Delta t\text{: time resolution, required } \Delta d\text{: distance resolution we want}}$
  - **If you want to have 1 mm resolution, you need to differentiate 3.3x10^{-12} sec**

LiDAR classification: Beam scanning methods

Rotating motor

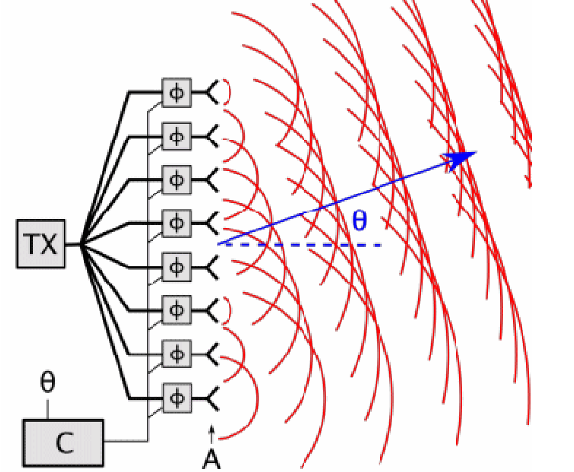


µ-mirror

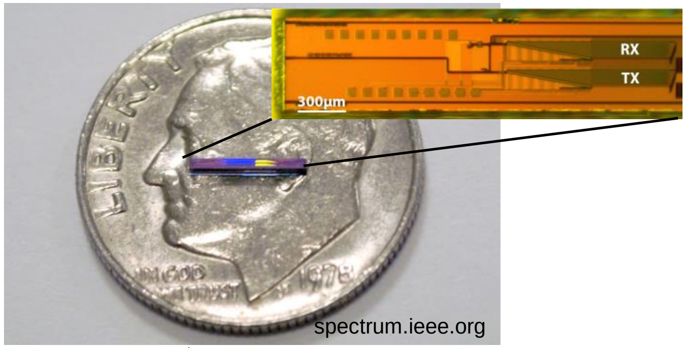


makeagif.com

Solid-state



davidgozzard.com/

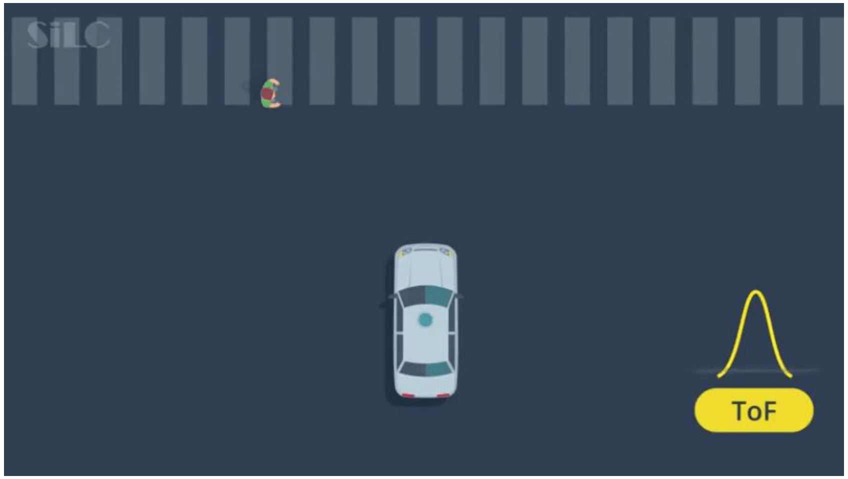


spectrum.ieee.org

Faster, smaller, more accurate, low cost (for mass production)

LiDAR classification: Timing

Time of Flight

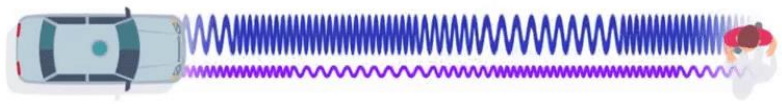


Video clip from https://www.youtube.com/watch?v=viW5n1xuTq8
SiLC Tehcnology Inc.

<Pros>
- **Simpler implementation (Low cost)**

<Cons>
- **Low resolution, smaller range**
- **Crosstalk**

FMCW

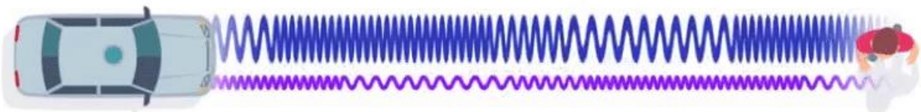


Video clip from https://www.youtube.com/watch?v=viW5n1xuTq8
SiLC Tehcnology Inc.

<Pros>
- **Higher accuracy, high sensitivity**
- **Longer range**
- **Direct velocity measurement (Dopper effect)**

<Cons>
- **Complex implementation (higher cost)**

FMCW LiDAR



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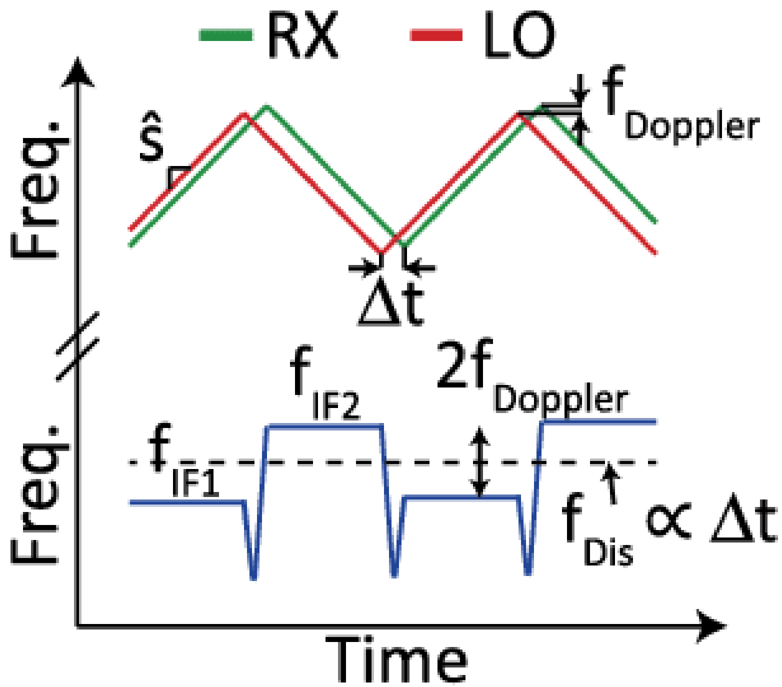
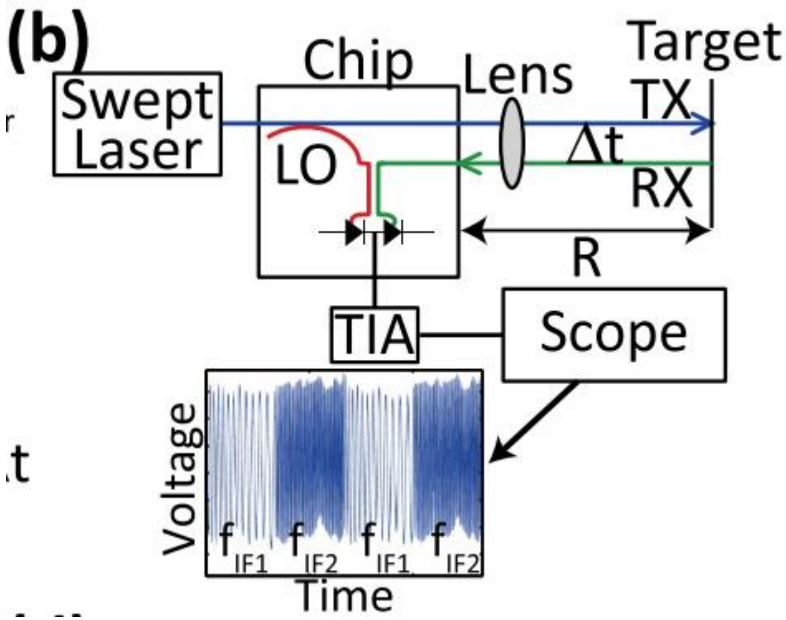
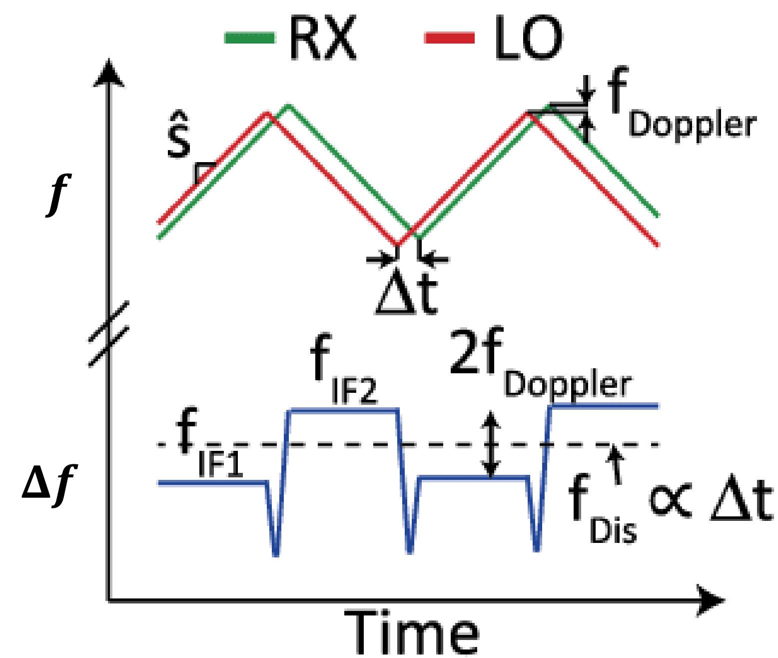


C. V. Poulton, A. Yaacobi, D. B. Cole, M. J. Byrd, M. Raval, D. Vermeulen, and M. R. Watts, "Coherent solid-state LIDAR with silicon photonic optical phased arrays," Opt. Lett. 42, 4091 (2017).

- **시간에 따라 레이저의 주파수(즉, 파장)를 선형적으로 변조 (up/down ramp)**
- **타겟에 맞고 돌아온 빛과 레이저의 주파수를 비교 → 걸린 시간 추출**

FMCW LiDAR





- **시간에 따라 레이저의 주파수(즉, 파장)를 선형적으로 변조 (up/down ramp)**
  - $f = at,\ a$: *just proportional constant*
- **타겟에 맞고 돌아온 빛과 레이저의 주파수를 비교 → 걸린 시간 추출**
  - $\Delta f = a\Delta t \rightarrow \Delta t = \frac{\Delta f_{laser}}{a}$
- $d = c\Delta t \rightarrow d = c\frac{\Delta f}{a}$, c: *speed of light*

C. V. Poulton, A. Yaacobi, D. B. Cole, M. J. Byrd, M. Raval, D. Vermeulen, and M. R. Watts, "Coherent solid-state LIDAR with silicon photonic optical phased arrays," Opt. Lett. 42, 4091 (2017).

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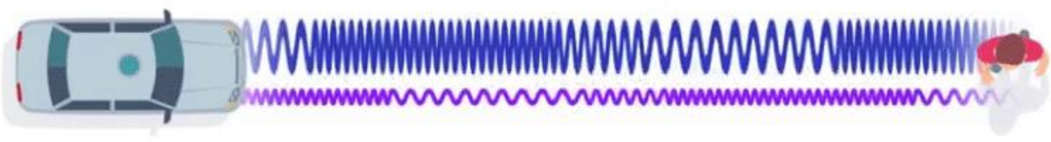

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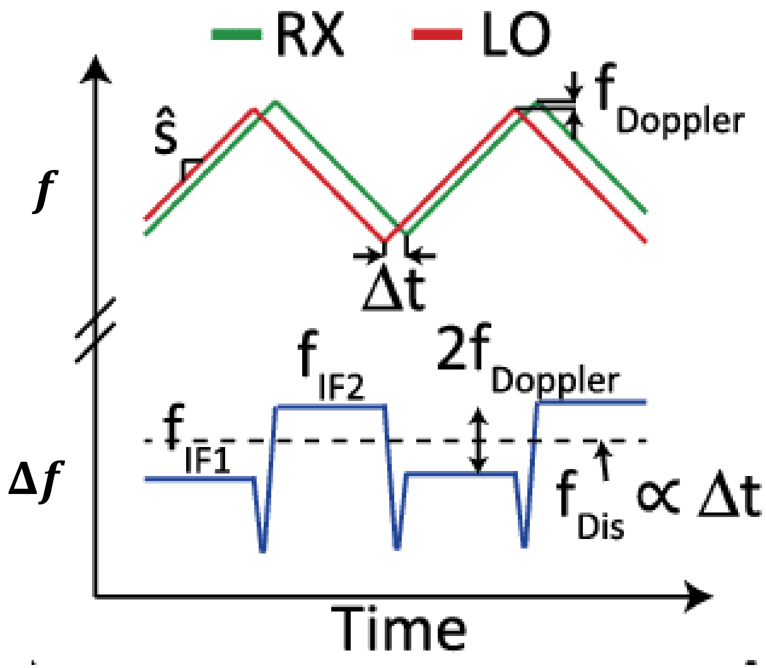
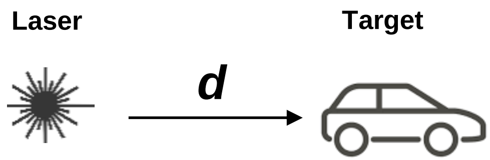
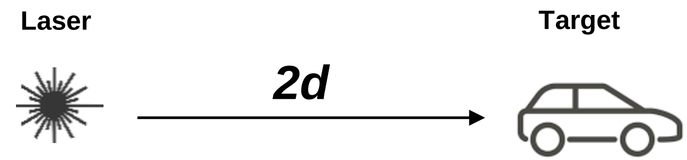
SiLC Tehcnology Inc.

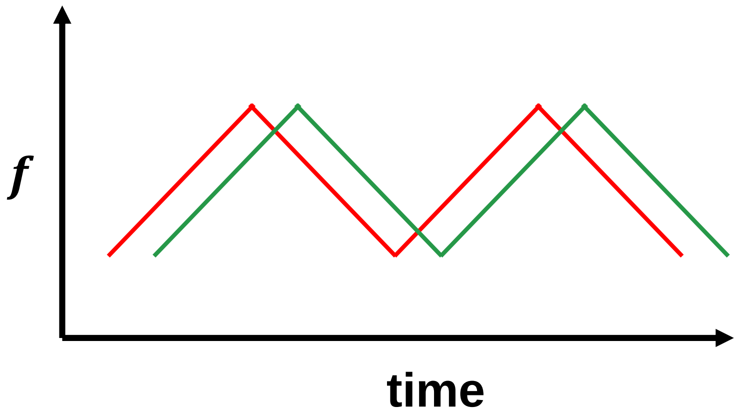


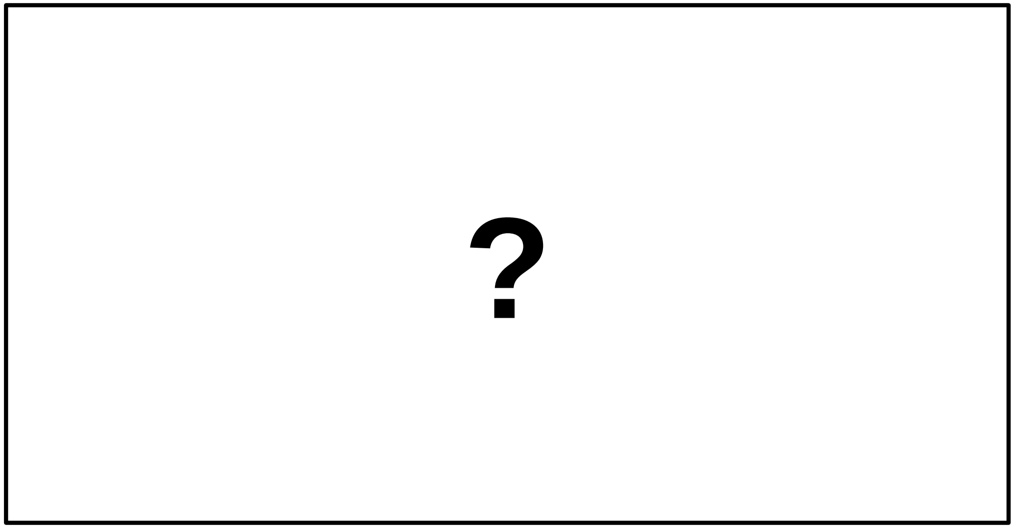
- $d = c\Delta t \rightarrow d = c\frac{\Delta f}{a}$, c: *speed of light*

Pop quiz



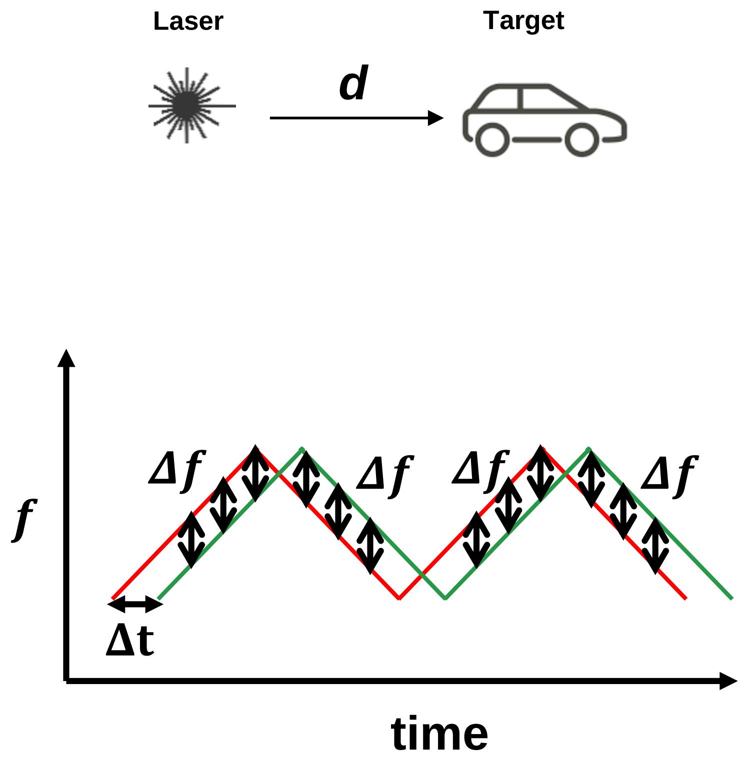


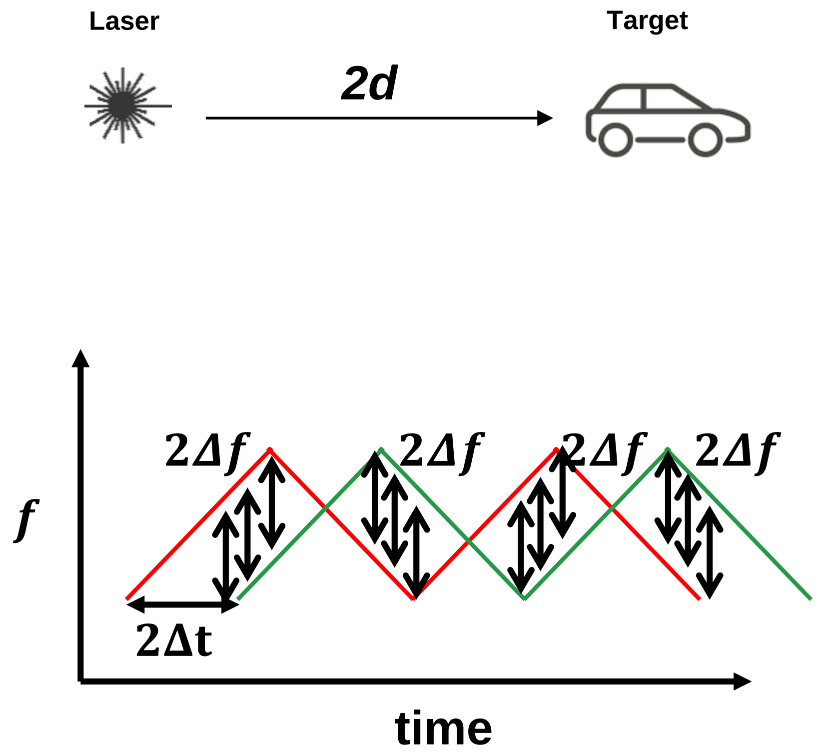




- **What is the profile of laser frequency graph if the distance becomes 2X?**

Pop quiz

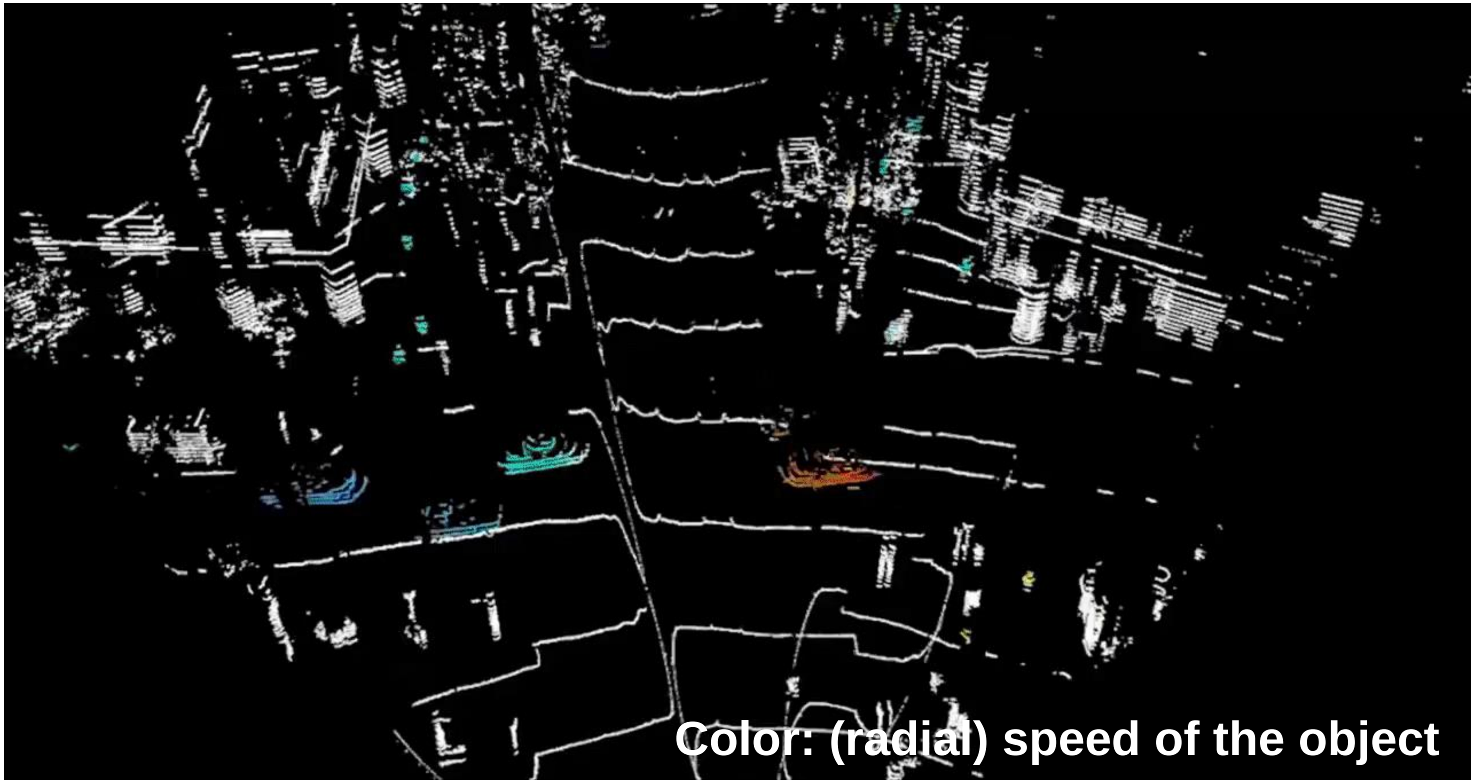




- **What is the profile of laser frequency graph if the distance becomes 2X?**

FMCW LiDAR can also measure speed directly!

Blackmore LiDAR

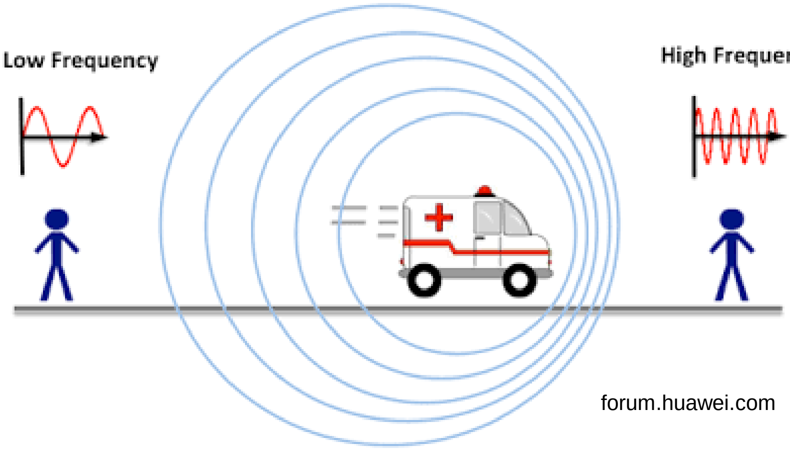


https://www.youtube.com/watch?v=AASycVyV4HA&t=6s

- **You can also measure speed by differentiating the distance, but it is much less accurate**
  - $v = \frac{dx}{dt}$, **what happen if there is noise in x?**

Doppler effect in sound wave

Doppler effect in sound



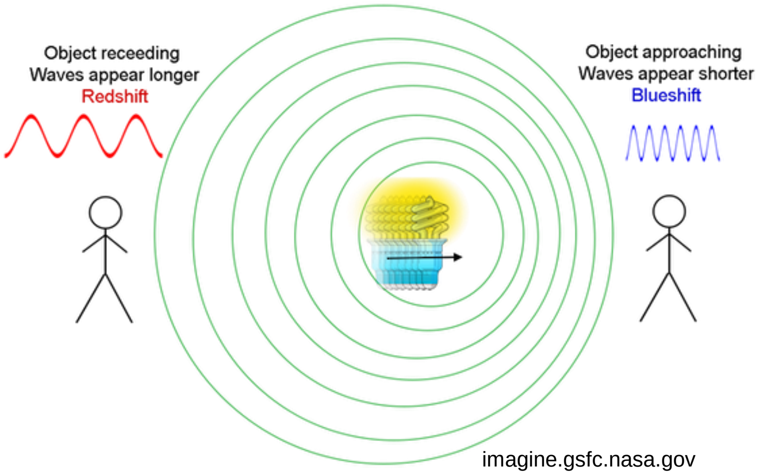
$$f = \frac{c + v_r}{c + v_s} f_0$$

c: *speed of wave*
v_r: *speed of reciever (towards source)*
v_s: *speed of source (away from receiver)*

- **Frequency of wave shifts when the source moves relative to the listener**

Doppler effect in light (EM wave)

Doppler effect in EM wave



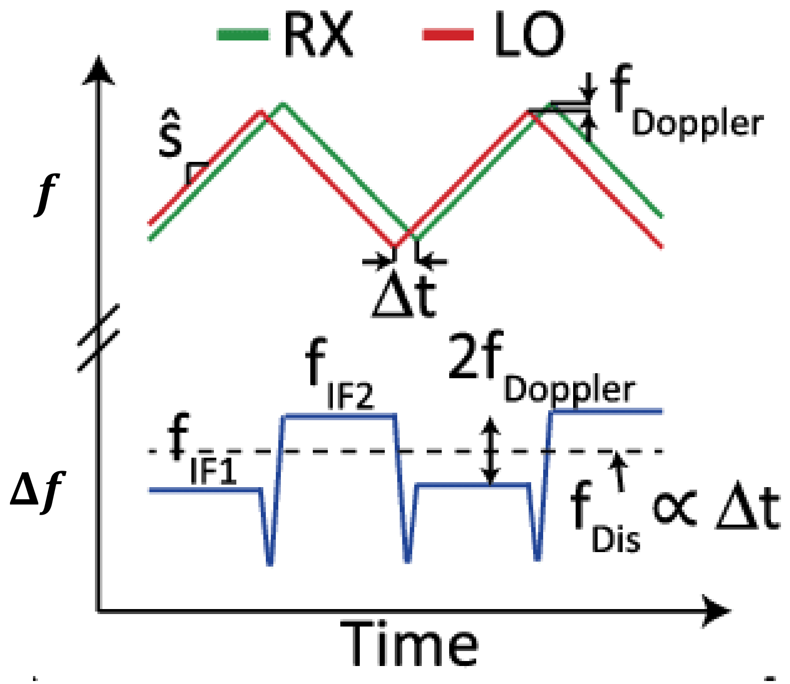
imagine.gsfc.nasa.gov

$$f = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}\, f_0$$

c: *speed of wave* (*light*)
v: *speed of source relative to receiver* (*approaching*)

- **When I walk toward you, you look little more bluish….**

Doppler effect in LiDAR



- **Can we actually measure it??**

Pop quiz I

- **If you walk towards me 1 m/s with red laser (430 THz), what is the frequency of the laser I observe?**

$$f = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} f_0$$

$$c: speed\ of\ wave\ (light)$$
$$v: speed\ of\ source\ relative\ to\ receiver\ (approaching)$$

$$f_0 = 4.3 * 10^{14}\ Hz$$

$$f = \sqrt{\frac{1+\frac{1m/s}{c}}{1-\frac{1m/s}{c}}} * f_0 = 4.3000000143 * 10^{14}\ Hz$$

$$\Delta f = 1.43 * 10^{6}\ Hz = 1.43 MHz$$

Pop quiz 2

- **If you walk towards me 2 m/s with red laser (430 THz), what is the frequency of the laser I observe?**

$$f = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}f_0$$

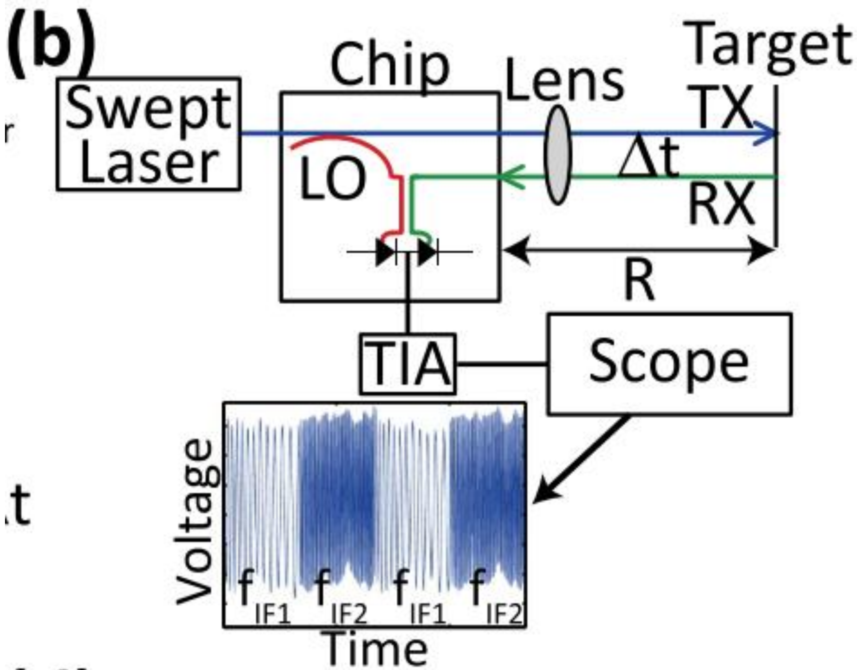
$$c: speed\ of\ wave\ (light)$$
$$v: speed\ of\ source\ relative\ to\ receiver\ (approaching)$$

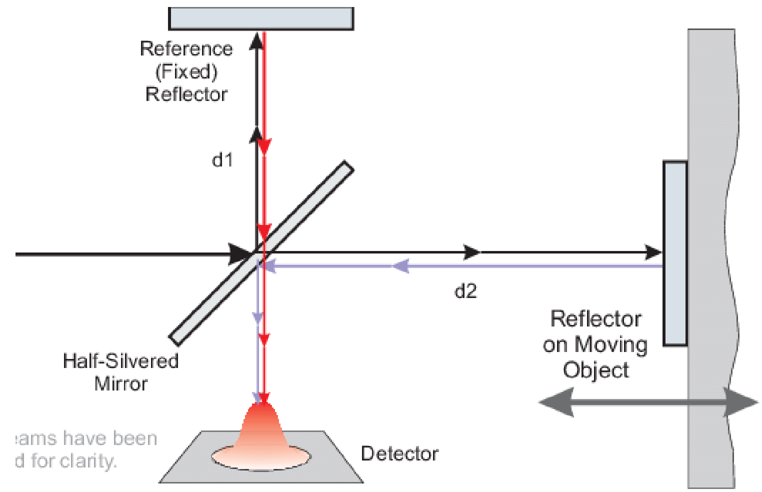
$$f_0 = 4.3 * 10^{14}\ Hz$$

$$f = \sqrt{\frac{1+\frac{2m/s}{c}}{1-\frac{2m/s}{c}}} * f_0 = 4.3000000287 * 10^{14}\ Hz$$

$$\Delta f = 2.87 * 10^6\ Hz = 2.87MHz$$

How do we measure the frequency shift??

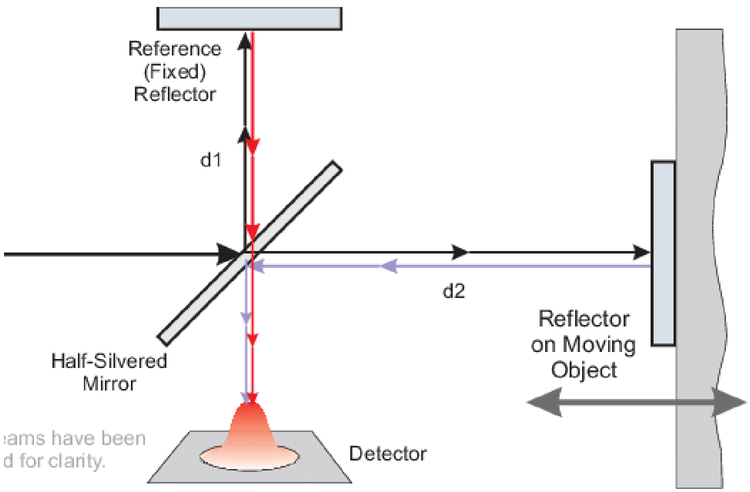




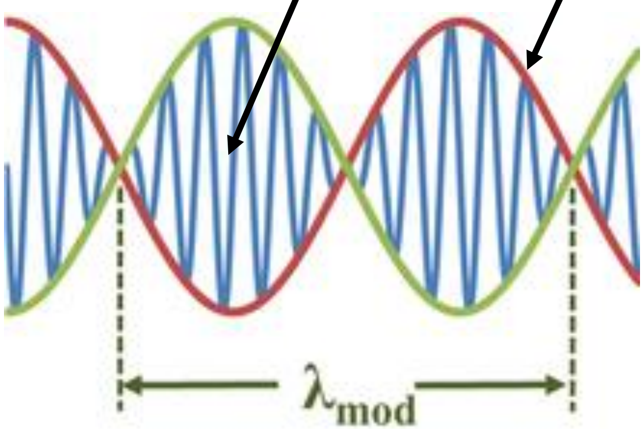
A tutorial on laser interferometry for precision measurements

- **1m/s → $1.43MHz$ (cf. FM radio frequency ~100 MHz)**
- **Beat (add) the RX signal with LO signal**
  - $\sin(2\pi f_0 t) + \sin(2\pi(f_0 + \Delta f)t) = 2\underbrace{\sin[2\pi(f_0 + \frac{\Delta f}{2})t]}_{\text{Carrier}}\overbrace{\sin[2\pi\frac{\Delta f}{2}t]}^{\text{Envelope}}$
- **Just like the FM radio (envelop detection)!**

How do we measure the frequency shift??



A tutorial on laser interferometry for precision measurements



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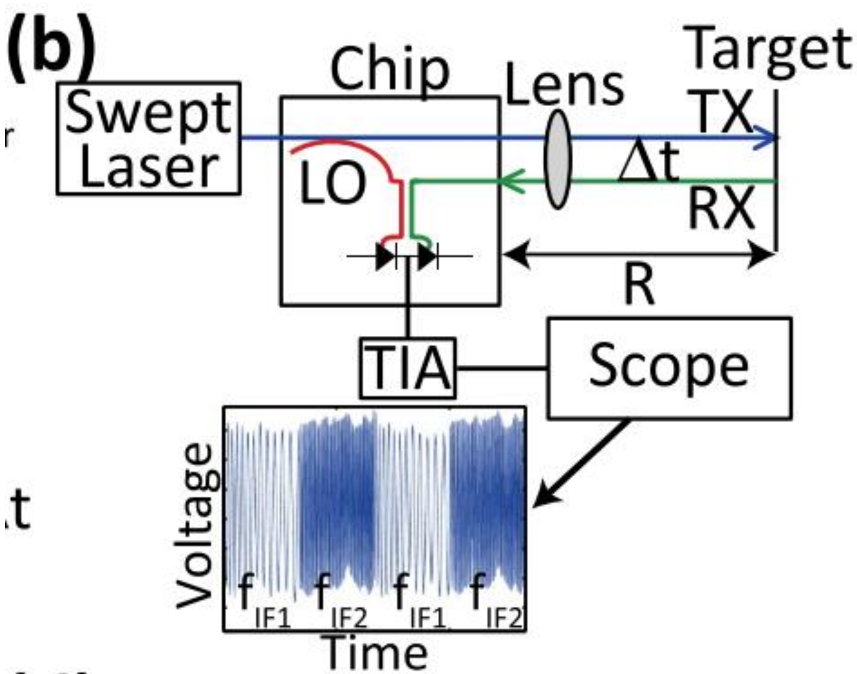
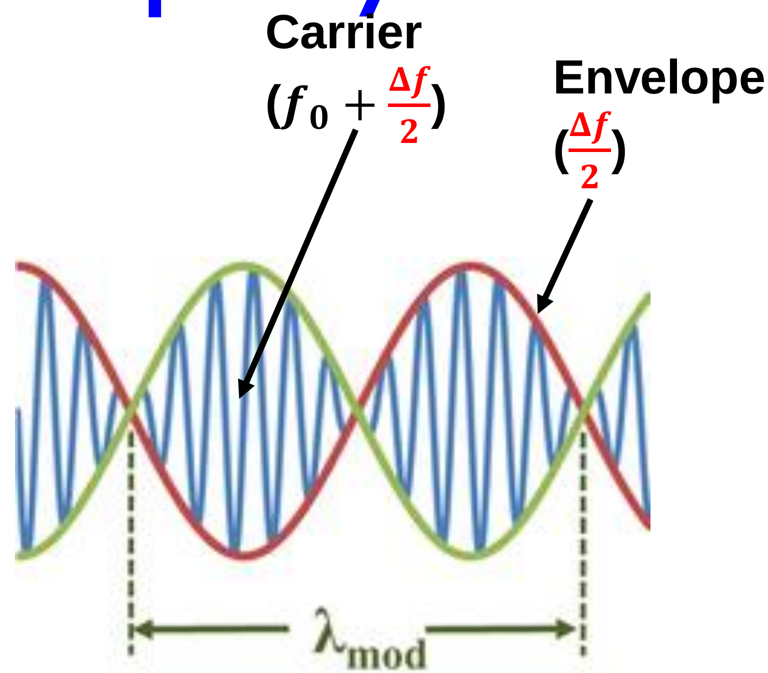
How do we measure the frequency shift??





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- **Just like the FM radio (envelop detection)!**

Cf. FM radio

	FM (MHz)			AM (kHz)	
1	89.1	KBS2 음악 FM	1	603	KBS 제2라디오
2	89.7	원음방송	2	711	KBS 제1라디오
3	91.9	MBC 음악 FM	3	792	SBS (AM Stereo)
4	93.1	KBS1 음악 FM	4	837	CBS
5	93.9	CBS 음악 FM	5	900	MBC
6	94.5	YTN 라디오	6	1188	FEBC 극동방송
7	95.1	TBS 교통방송			
8	95.9	MBC 표준 FM			
9	97.3	KBS1 표준 FM			
10	98.1	CBS 표준 FM			
11	99.1	국악방송			
12	100.5	인천교통방송			
13	101.1	국군방송			
14	101.9	불교방송			
15	102.7	AFKN			
16	103.5	SBS 러브 FM			
17	104.5	EBS 교육라디오			
18	105.3	평화방송			
19	106.1	KBS2 표준 FM			
20	106.9	극동방송			
21	107.7	SBS 파워 FM			

- **1m/s → $1.43MHz$**
- **2m/s → $2.87MHz$**
- **Piece of cake to distinguish the two…**

http://blog.naver.com/PostView.nhn?blogId=joinhot&logNo=100142491727&parentCategoryNo=6&categoryNo=&viewDate=&isShowPopularPosts=true&from=search

Photonics for Intelligence -Lecture 2: Optical phased array, Photonic integrated circuits-

Prof. Sangyoon Han

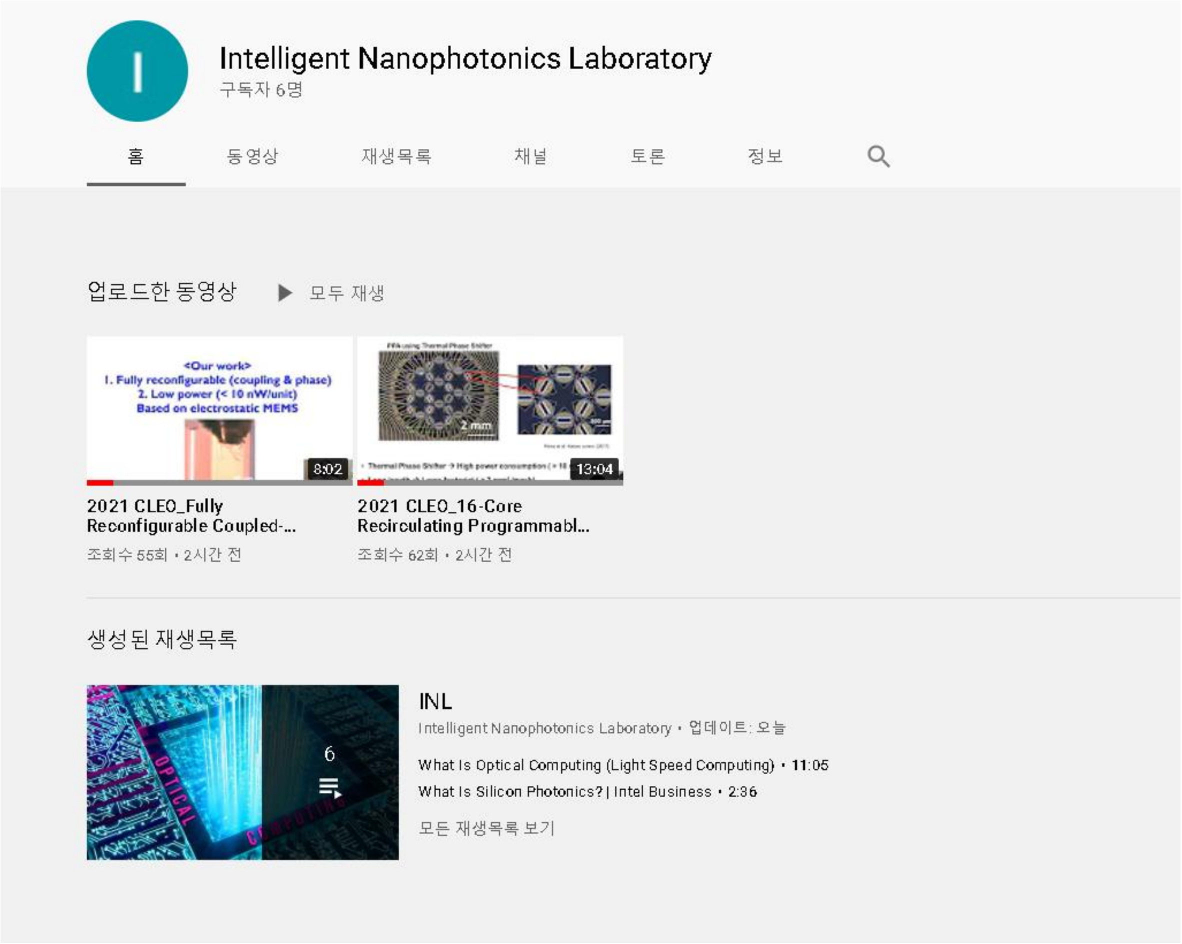
DGIST class material

Spring 2021

200 µm

Background image: silicon photonic switch fabricated by Prof. Sangyoon Han

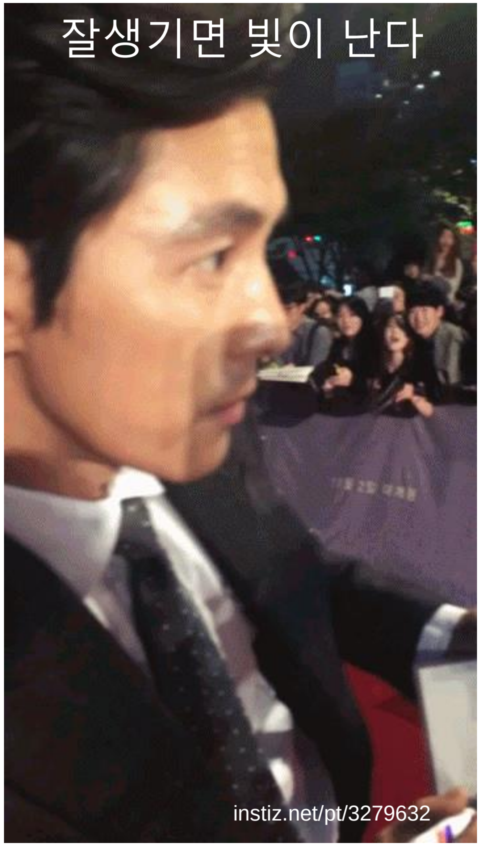
연구실 유튜브 채널 개설!



- 채널 주소: https://www.youtube.com/channel/UC9xRW1kJITc1s1BsiSC_b7A
- 연구실에서 진행되는 연구 관련 동영상 업로드
- 연구실 홈페이지 주소: https://www.intelligent-photonics.com/

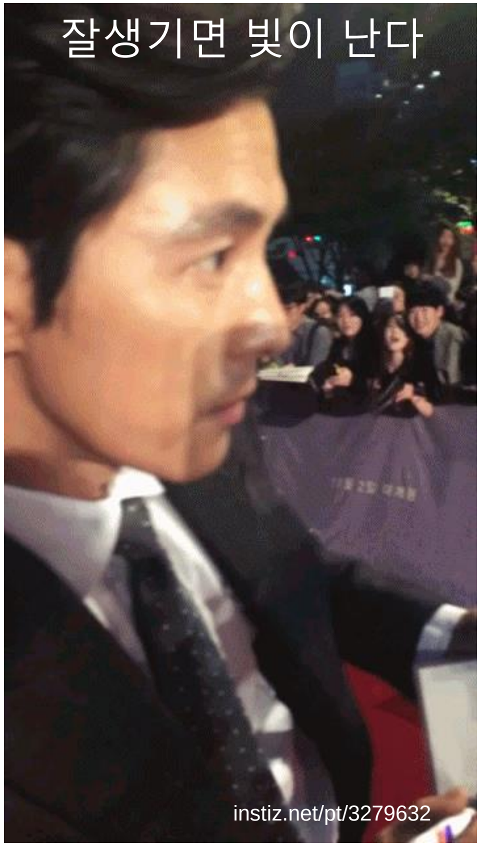
Trivia

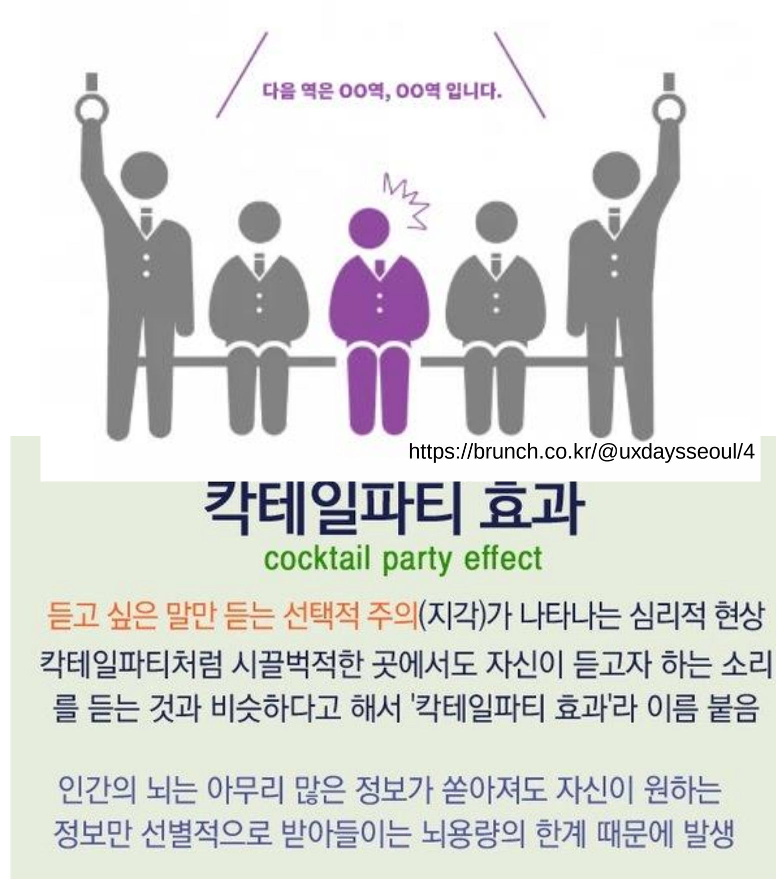
Let there be light!



- **여러 종교에서 나오는 빛에 대한 은유**
  - **"빛과 소금", "빛이 있으라", "부처님의 광명" 등등**
- **인간이 받아들이는 외부 정보의 70~80%는 시각 정보. 우연이라고 보기에는…**
- **"…인간의 상상에서 나오는 것들은 언제나 시각적인 형태를 갖기 마련이다…", 칼 융, 우나 살루스-대자유에 이르는 길**

후광이란 뭘까??





m.post.naver.com

- **후광이란 칵테일파티 효과의 시각 버전?**

Nobel Prizes related to Photonics
(~ every 3 years)

1902
Physics
Lorentz and Zeeman
The Zeeman Effect, Electron Oscillator Model

1903
Physiology or Medicine
Finsen
Phototherapy – use of UV light to treat Lupus

1907
Physics
Michelson
The Michelson Interferometer & Precision Measurements

1908
Physics
Lippmann
Colour Photography based on Interference

1911
Physiology or Medicine
Gullstrand
Description of the Refractive Optics of the Eye

1912
Physics
Dalén
Solar-based regulator for buoys and lighthouses

1918
Physics
Planck
Energy Quanta

1919
Physics
Stark
The Stark Effect

1921
Physics
Einstein
Photoelectric Effect & services to theoretical physics

1922
Physics
Bohr
Atomic Structure and the nature of radiation

1923
Physics
Millikan
Elementary Charge and the Photoelectric Effect

1927
Physics
Compton
The Compton Effect

1930
Physics
Raman
Raman scattering

1932
Physics
Heisenberg
Creation of Quantum Mechanics

1933
Physics
Schrodinger and Dirac
New Productive Forms of Atomic Theory

1945
Physics
Pauli
Pauli Exclusion Principle

1953
Physics
Zernike
Phase Contrast Microscope

1954
Physics
Born
Statistical Interpretation of the Wavefunction

1955
Physics
Lamb
Fine structure of the H Spectrum (Lamb Shift, QED)

1964
Physics
Townes, Basov, and Prokhorov
Maser-Laser Principle

1966
Physics
Kastler
Precision studies of optical resonances

1967
Physiology or Medicine
Granit, Hartline, and Wald
Physiological and chemical visual processes in the eye

1967
Chemistry
Eigen, Norrish, and Porter
Flashlamp Pump-Probe Studies of Chemical Reactions (μs)

1971
Physics
Gabor
Holography

1981
Physics
Bloembergen and Schawlow
Laser Spectroscopy

1981
Physiology and Medicine
Hubel and Wiesel
Information Processing in the Visual System

1989
Physics
Ramsey, Dehmelt, and Paul
Atomic Clocks, the Ion Trap

1997
Physics
Chu, Cohen-Tannoudji, and Phillips
Laser Cooling and Trapping

1999
Chemistry
Zewail
Femtochemistry

2000
Physics
Alferov and Kroemer
Optoelectronics, Semiconductor Heterostructures

2001
Physics
Cornell, Ketterle, and Wieman
Bose Einstein Condensation

2005
Physics
Glauber, Hall, and Haensch
Quantum Optics, Spectroscopy, Optical Frequency Comb

2008
Chemistry
Shimomura, Chalfie, and Tsien
Green Fluorescent Protein GFP

2009
Physics
Kao, Boyle, and Smith
Optical Fiber Communications ; Imaging and the CCD

2012
Physics
Haroche and Wineland
Individual Quantum Systems

2014
Physics
Akasaki, Amano, and Nakamura
The Blue LED and Energy-Saving White Light Sources

2014
Chemistry
Betzig, Hell, and Moerner
Super-resolution microscopy

2018
Physics
Ashkin, Mourou, and Strickland
Optical Tweezers & Biophotonics
Chirped Pulse Amplification

John M. Dudley, "Light, Lasers, and the Nobel Prize," Adv. Photon. 2(5) 050501 (10 October 2020)

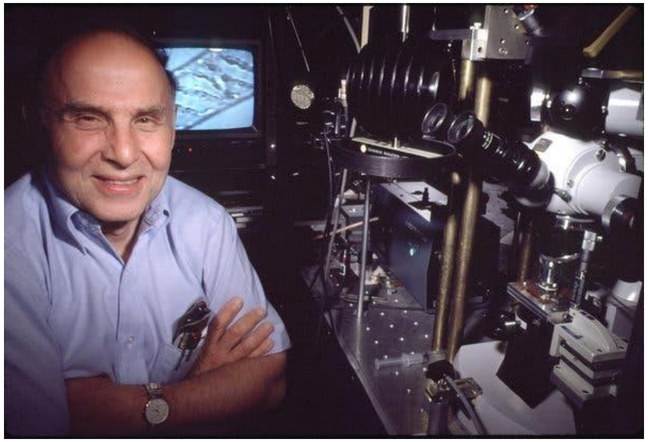
Optical tweezer, etc.

Trapping object using light

Trapping a particle using light

https://www.youtube.com/watch?v=BPN90U4yzBc&t=1s

Arthur Ashkin, Nobel prize, 2018



- **Light can exerts force on an object**
- **You can grab an object using light**

Optoelectronic tweezer

https://www.youtube.com/watch?v=Q7naTWc2whk&t=1s

Prof. Ming C. Wu
@ UC Berkeley
(my advisor)

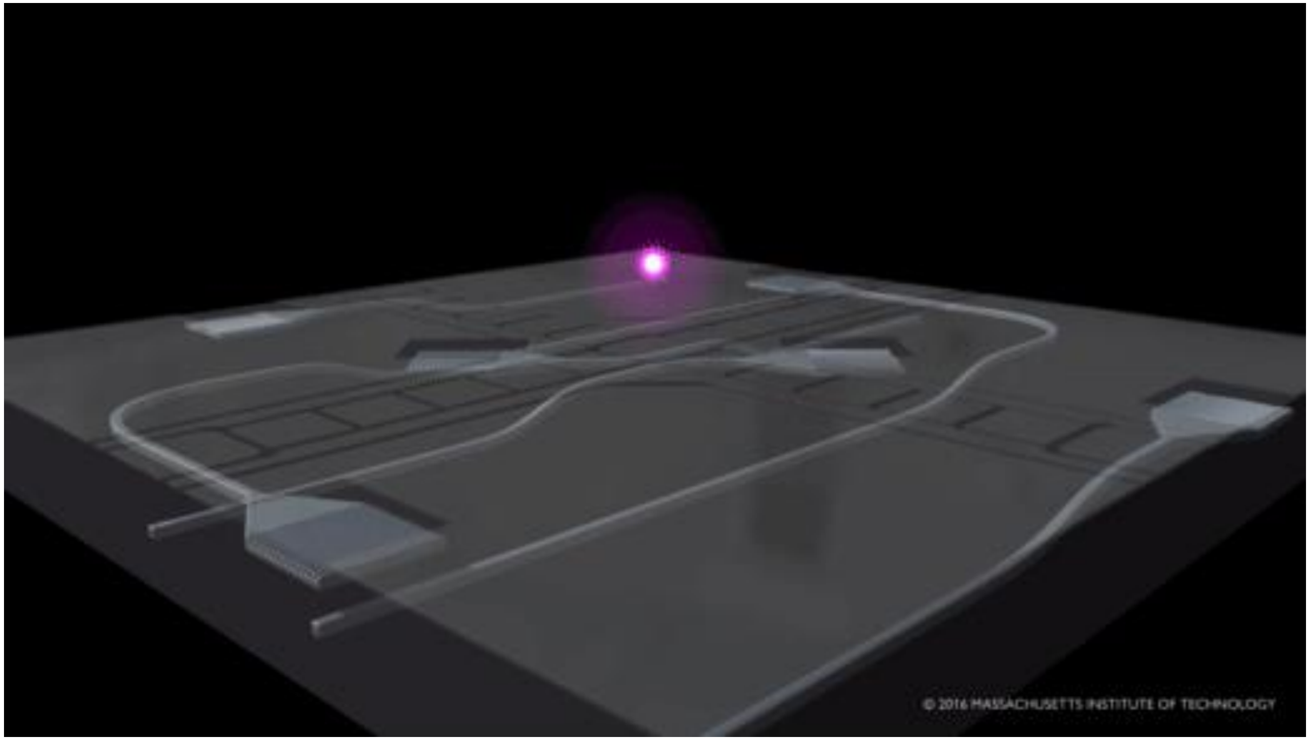
- **Based on optoelectrical phenomenon**
- **Move individual cells with light patters (cell sorting etc.)**
- **Berkeley light: spin-off company (Prof. Ming C. Wu)**

Berkeley Lights' Target Price Raised to $80 at Morgan Stanley After Earnings Beat, Forecasts $120 in Best Case

Morgan Stanley raised their stock price forecast on Berkeley Lights to $80 from $65, assigning an "Equal-weight" rating and said the leading digital cell biology company's top-line earnings beat in its first quarter was driven by robust system installs to cell therapy and CRO/CDMO customers and a strong recovery in recurring revenue of the expanding installed base.

Vivek Kumar
Nov 15, 2020 02:37 PM GMT

Ion trap for quantum computing (animation)

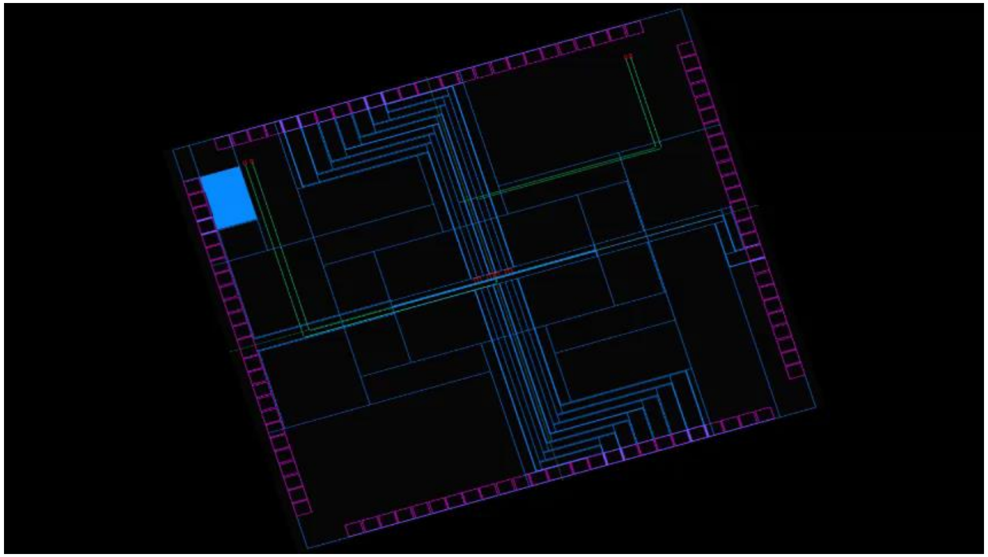


https://www.youtube.com/watch?v=UT3ev9OgkmY

- **Trap single ion (yes, single ion) with electric field**
- **Turn ion on/off using light**

전자(원자)를 가지고 하는 주판알 놀이

양자 컴퓨터



Mehta, K., Bruzewicz, C., McConnell, R. *et al.* Integrated optical addressing of an ion qubit. *Nature Nanotech* **11,** 1066–1070 (2016)

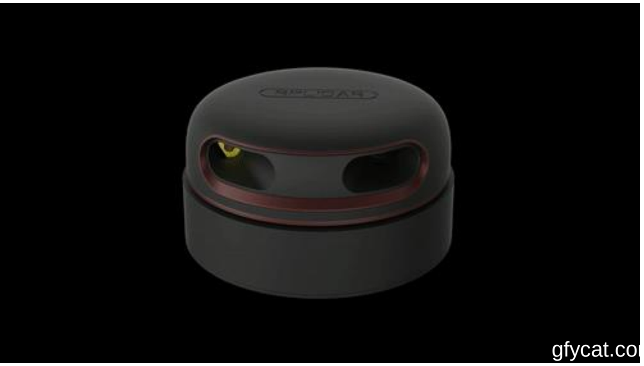
주판

- **Single ion is a very good qubit**
- **Quantum computer possible with multi-ion interactions**

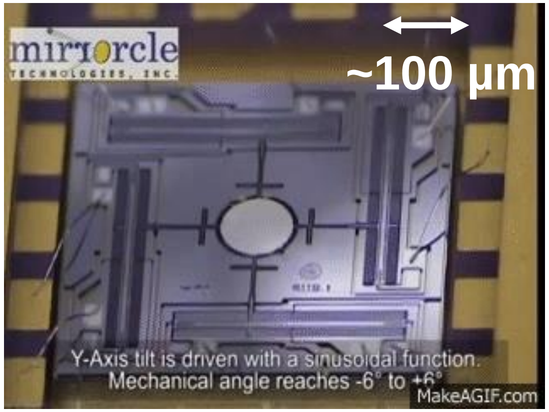
Optical phased array

LiDAR classification: Beam scanning methods

Rotating motor

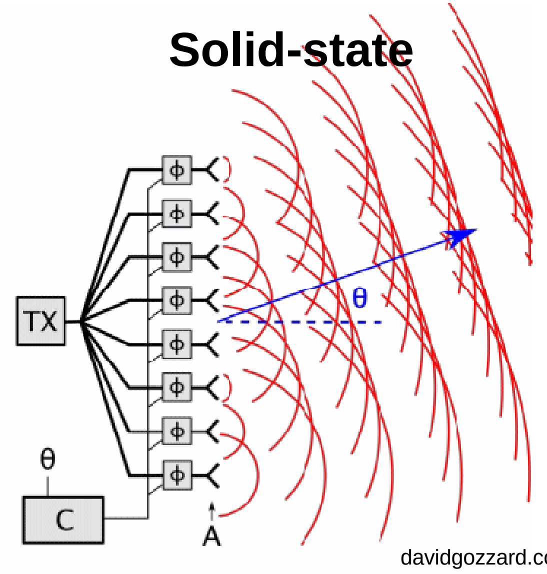


μ-mirror

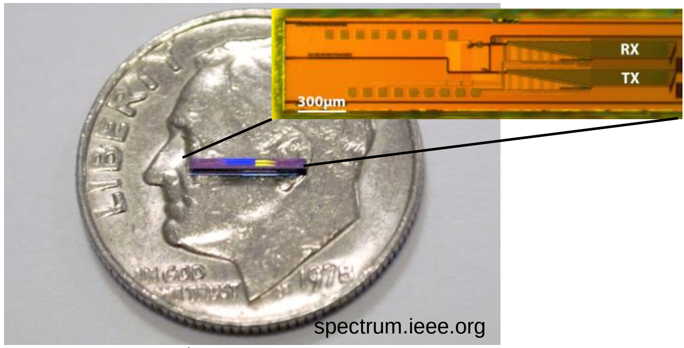


makeagif.com

Solid-state



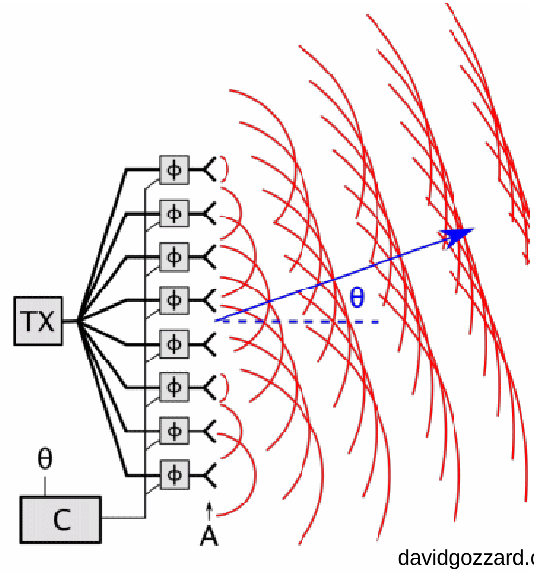
davidgozzard.com/



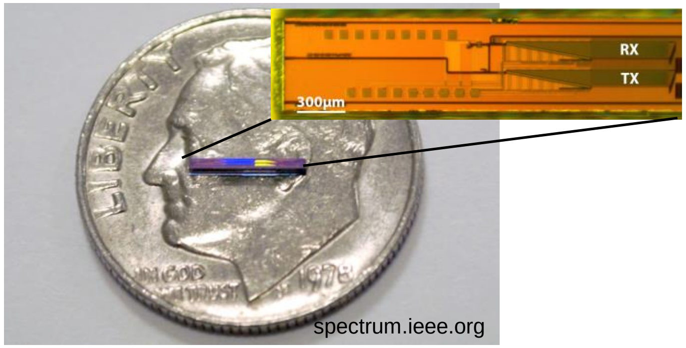
spectrum.ieee.org

Faster, smaller, more accurate, low cost (for mass production)

How phased array works?

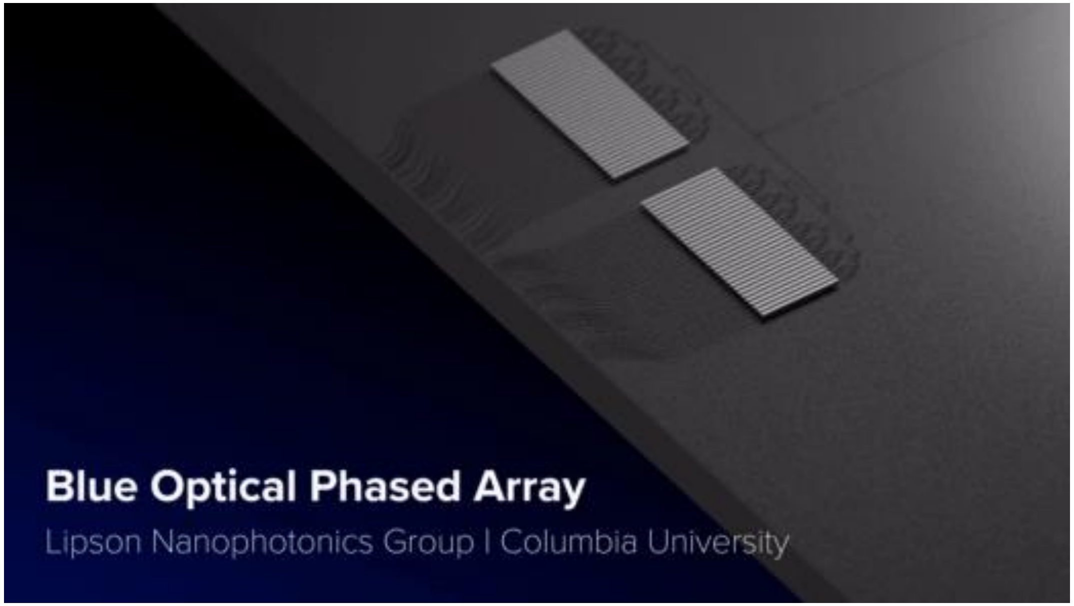


davidgozzard.com/



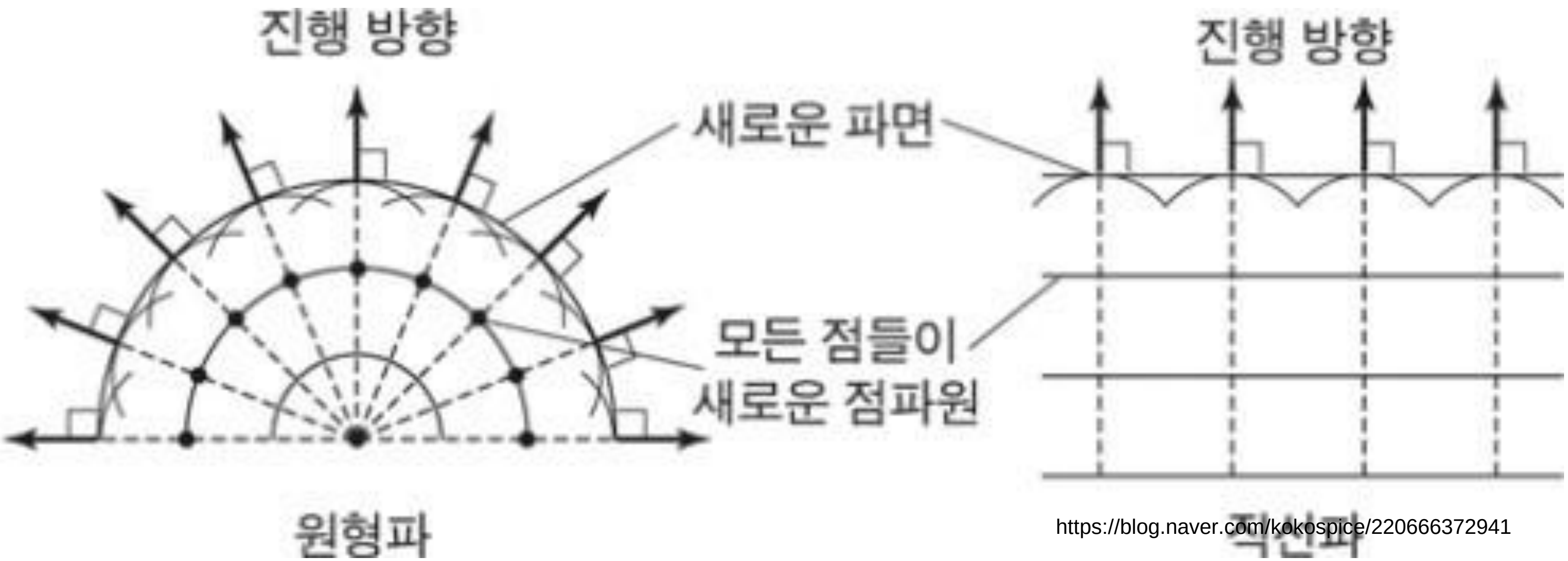
spectrum.ieee.org

Optical phased array on a chip

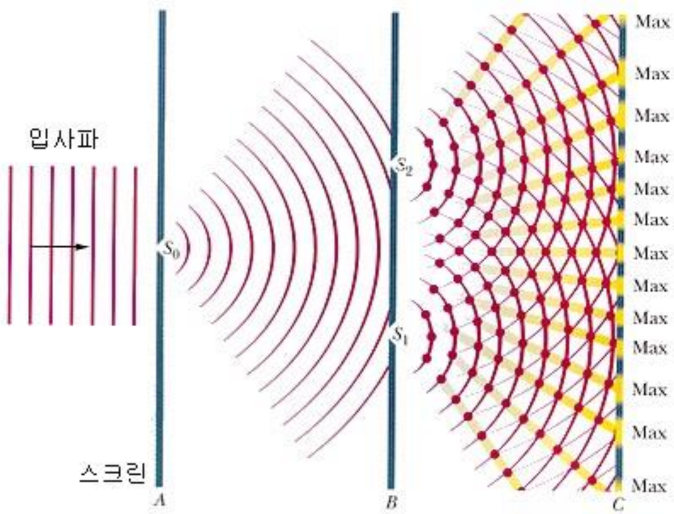


https://www.youtube.com/watch?v=xEqV879qDNE

Huygens principle (remember it?)



https://blog.naver.com/kokospice/220666372941

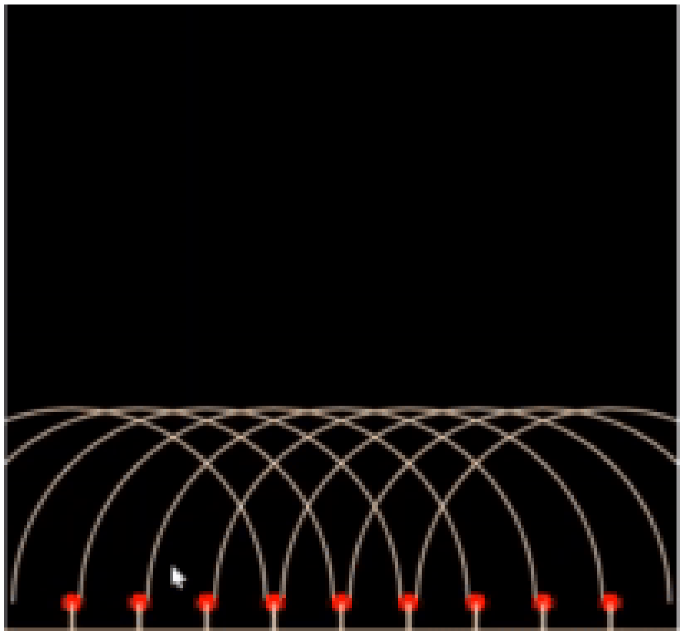


- 호이겐스의 원리
- 만약 우리가 각 점의 진동 순서를 조절 할 수 있다면?

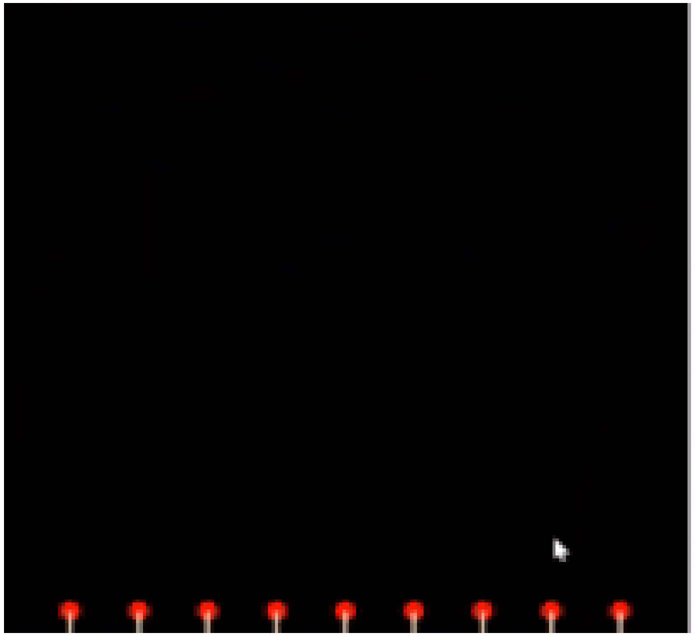
https://blog.naver.com/k
6372941

Huygens principle (animations)

수직 진행



비스듬한 진행

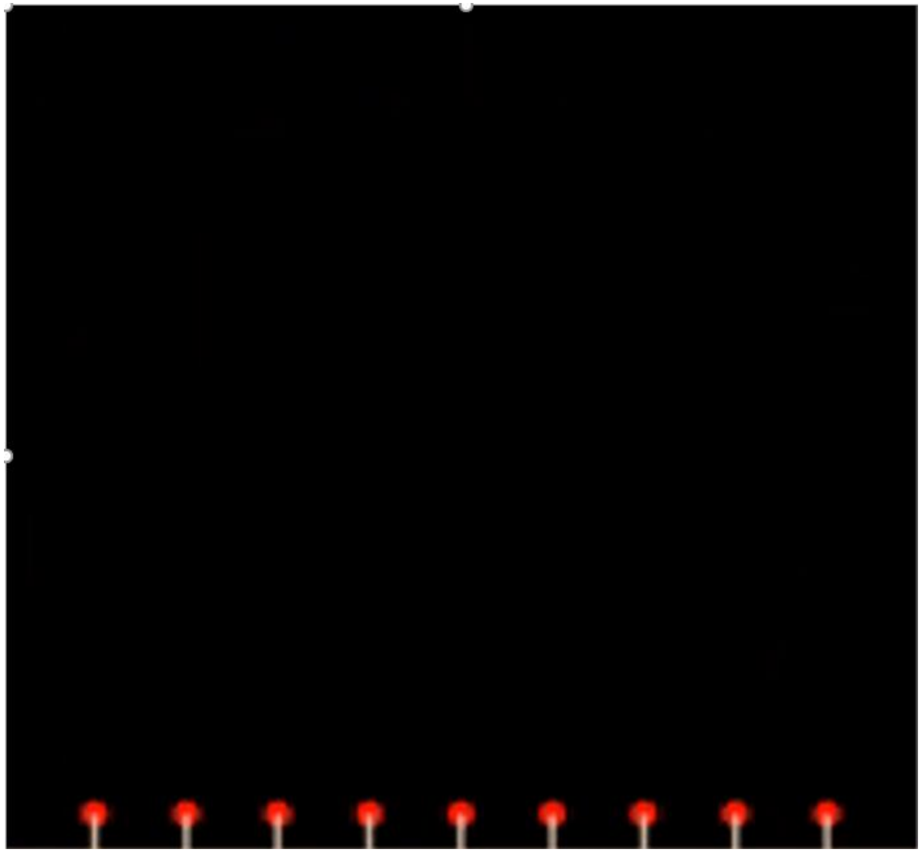


https://www.youtube.com/watch?v=vLmhzv_T-74

- 각 점에서 빛이 나가는 순서를 조절하면 원하는 방향으로 빛을 꺾을 수 있다!

Pop quiz

- 빛을 모으려면 (focusing), 어떤 순서로 빛을 켜야 할까요?



Pop quiz

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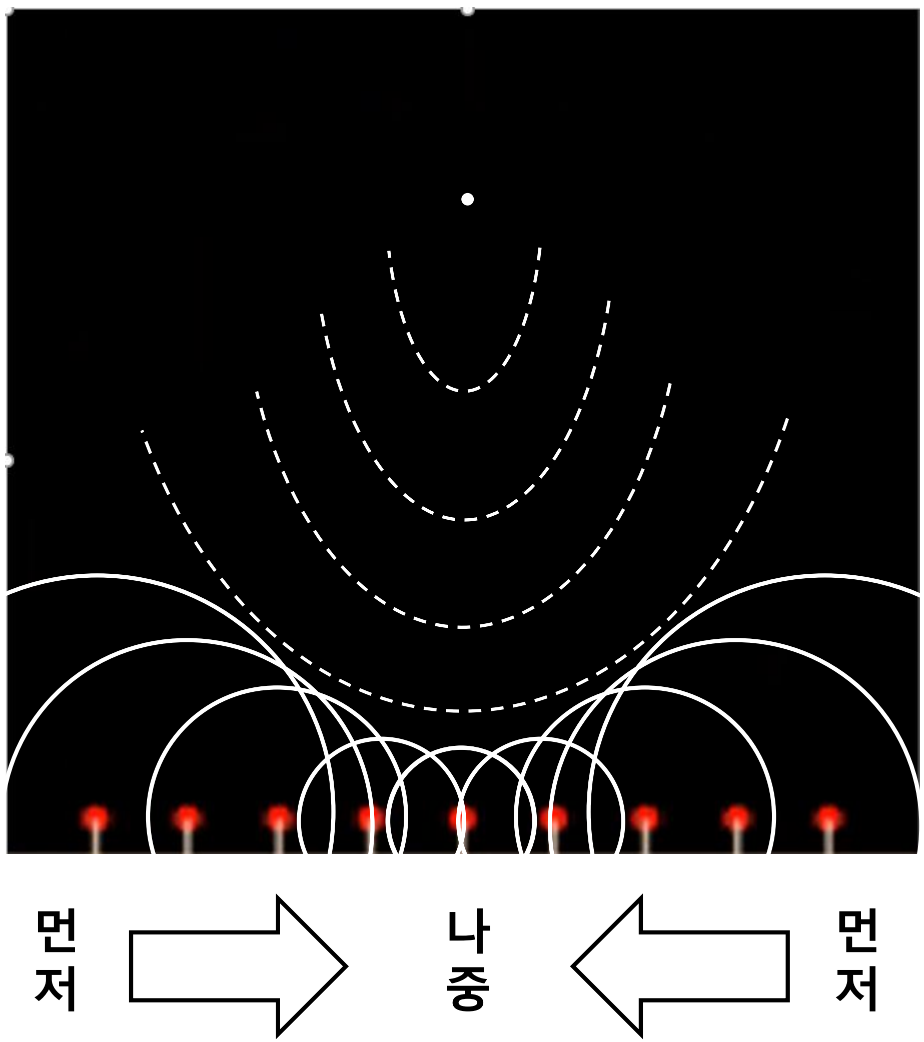
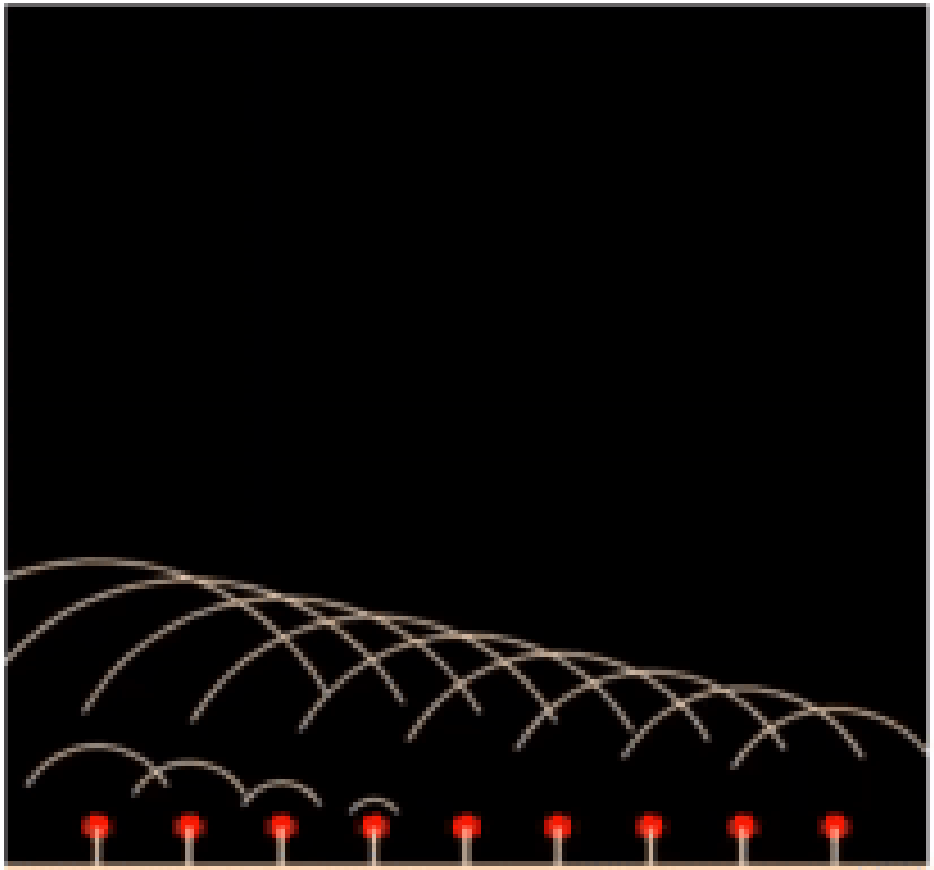


You now know how phased array work!

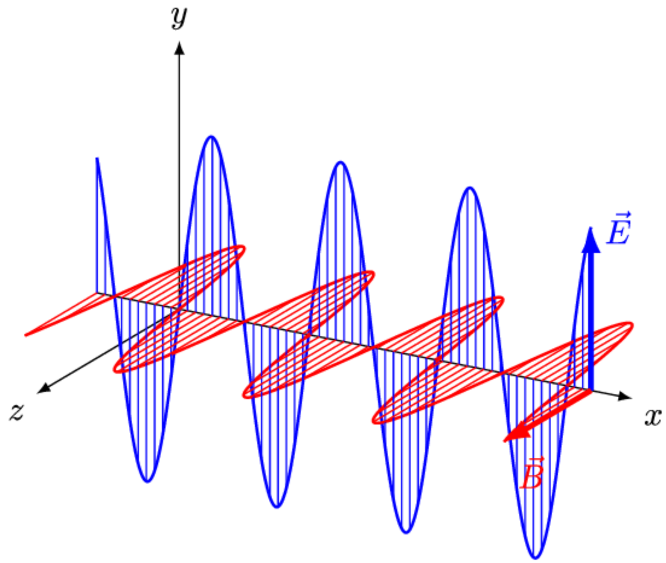


https://www.youtube.com/watch?v=vLmhzv_T-74

- **But how do you make it???**
- **Use photonic integrated circuits!**

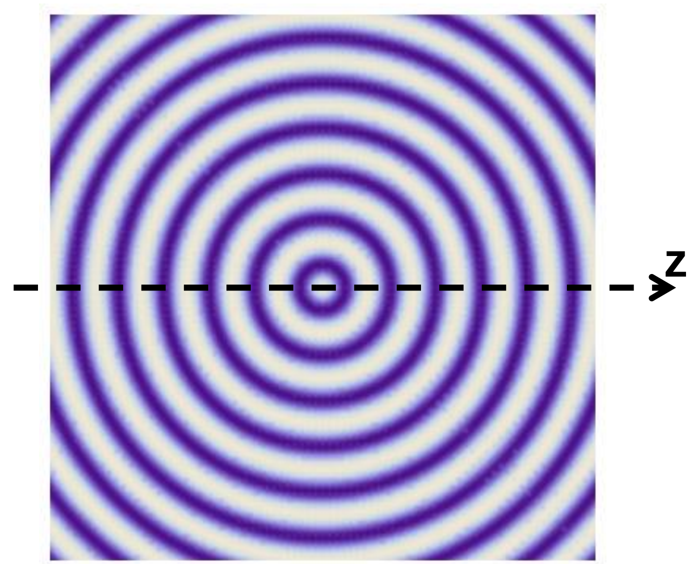
Propagation of light

Electromagnetic wave



And1mu

Wave video

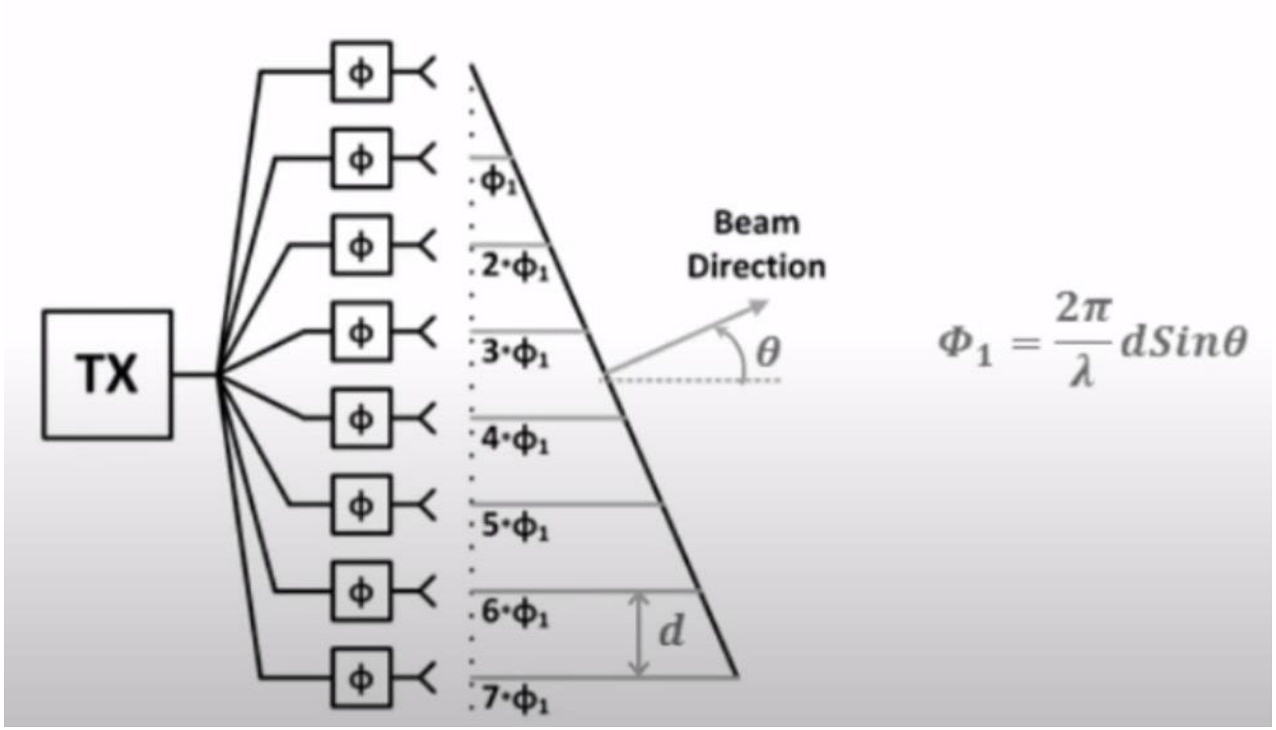


https://www.rakeshkapoor.us

$$E(z,t) = E_0 cos(kz - \omega t + \delta)$$

- **Light propagate in the form of**
  - $E(z,t) = E_0 cos(kz - \omega t + \delta)$
- **Can you visualize it?**

Technical details



https://www.youtube.com/watch?v=l4OwU1p8_tE

$$E(z,t) = E_0 cos(kz - \omega t + \phi)$$

- **But how do you make it???**
- **Use photonic integrated circuits!**

Photonic Integrated Circuits (PIC)

Photonic Integrated Circuits (PICs)

Bulk optical system

spar3d.com

Photonic integrated circuits (PIC)

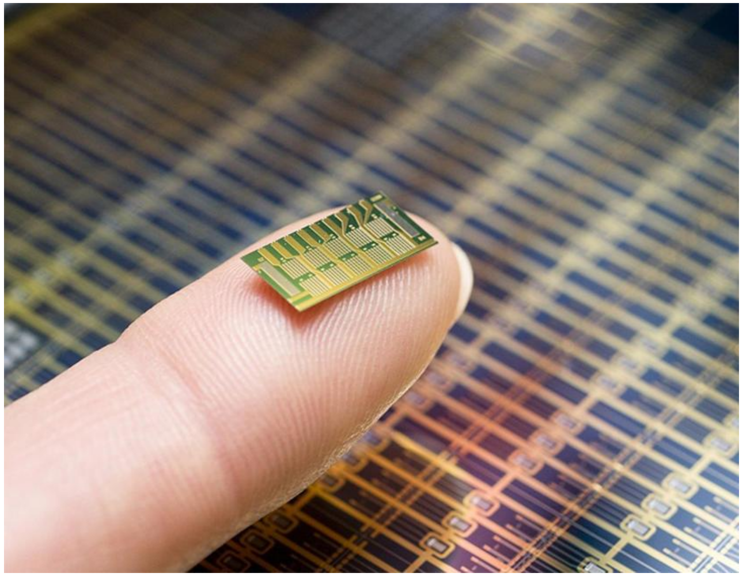


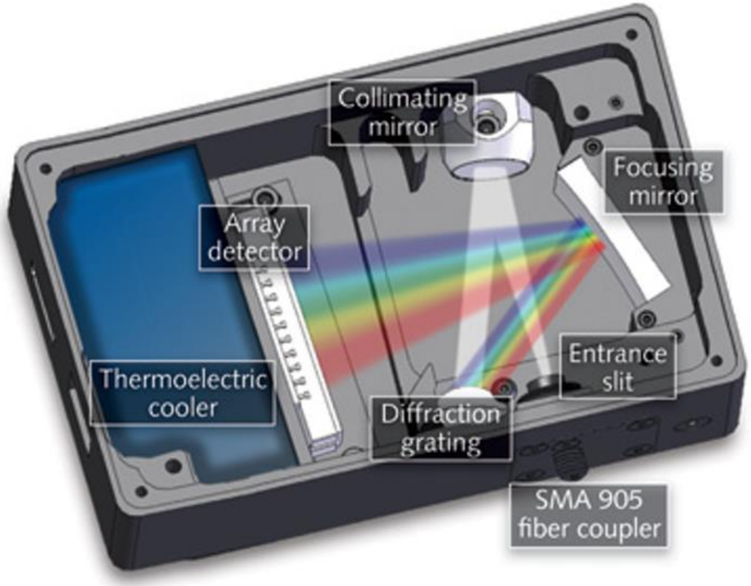
image source: cnet

- ***"Photonics on a chip"***
- **Integrated with electronics**
- **Advantages in *<u>performance, density, complexity, speed, size, cost</u>* and more**

Bulk optical systems (= free-space systems)

Bulk optic spectrometer

reddit.com/

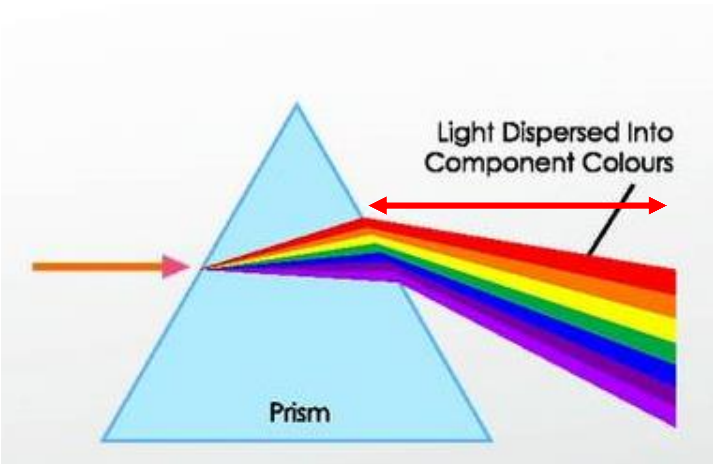


laserfocusworld.com

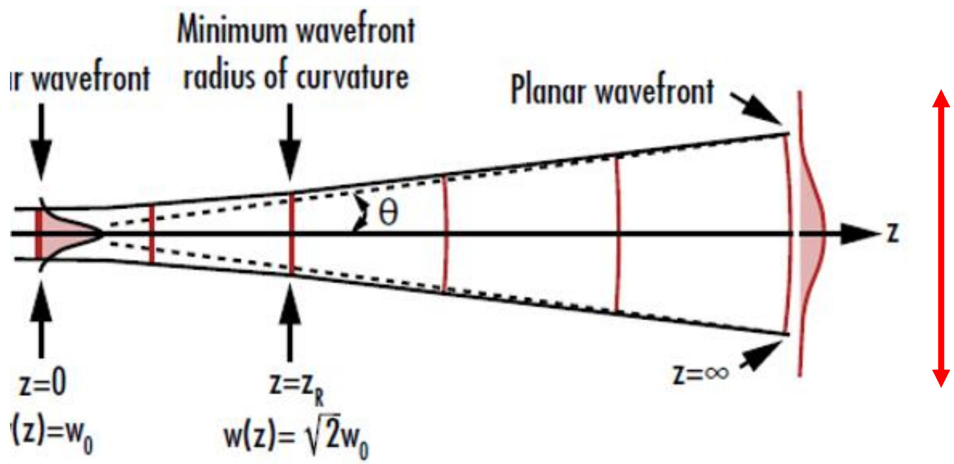
- **Lenses, mirrors, prisms, light source, detectors**
- **+ free (empty) spaces**

Why there is "free-space"?

Dispersion of light



Diffraction of light

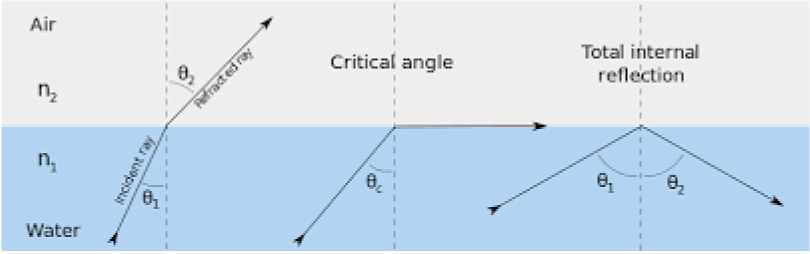


$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_\mathrm{R}}\right)^2}$$

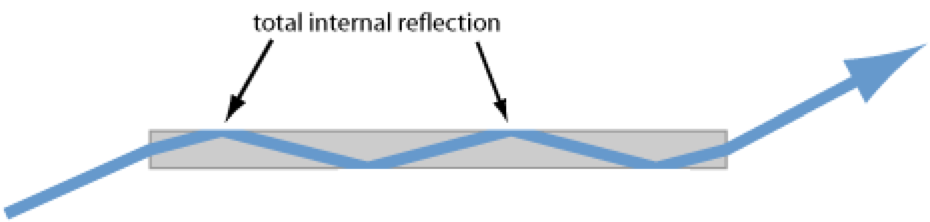
- **The miniaturization of system is fundamentally limited by <u>dispersion and diffraction</u> of light**

Optical waveguide

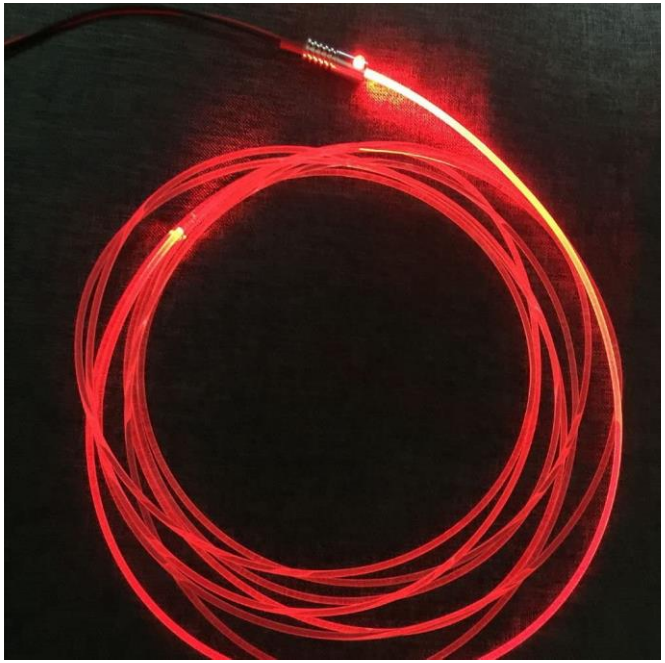
Total internal reflection (TIR)



Inside waveguide



Optical fiber

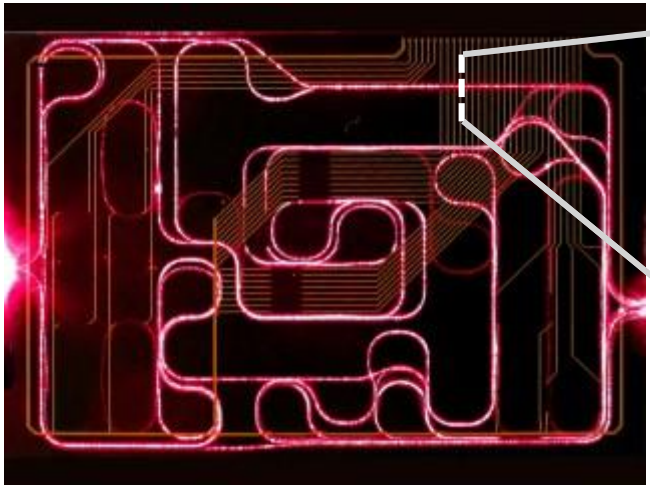


amazon.com

- **Light is guided by TIR**
- **Eliminate diffraction**

Optical Waveguides on PIC

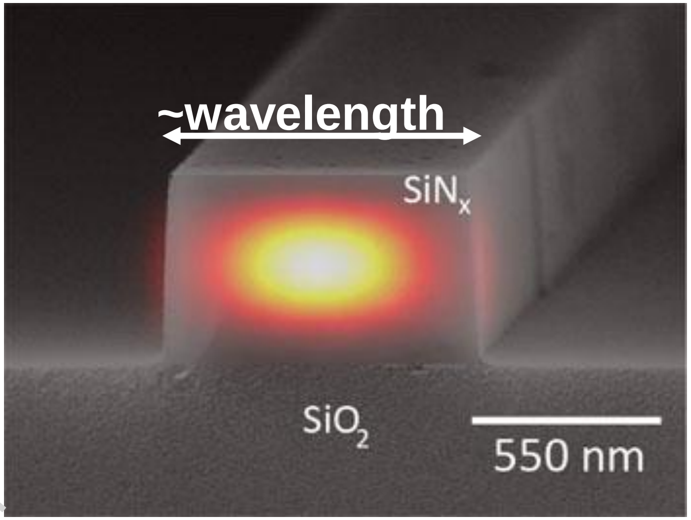
PIC



www.phiconference.com

~cm

Waveguide cross-section

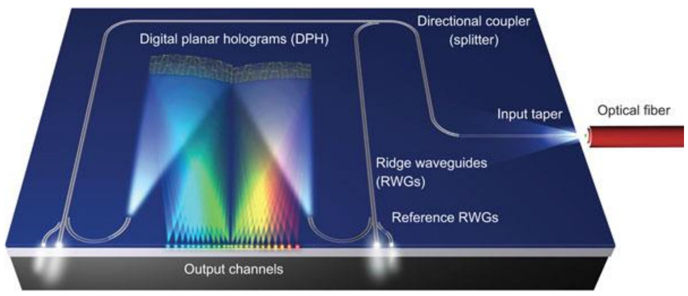


nist.gov

- **Light is guided by total internal reflection (TIR)**
- **Can be miniaturized down to ~wavelength (400 nm ~ 2 um)**

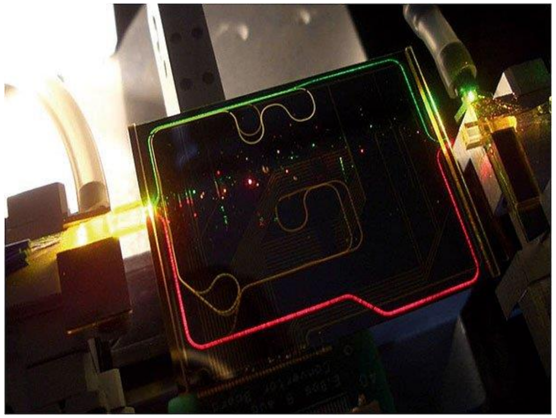
Miniaturization Using Waveguide

Spectrometer on a chip

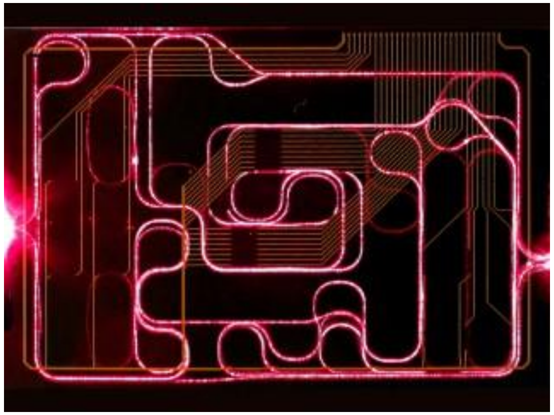


researchgate.net

Actual PIC images



cmmmagazine.com



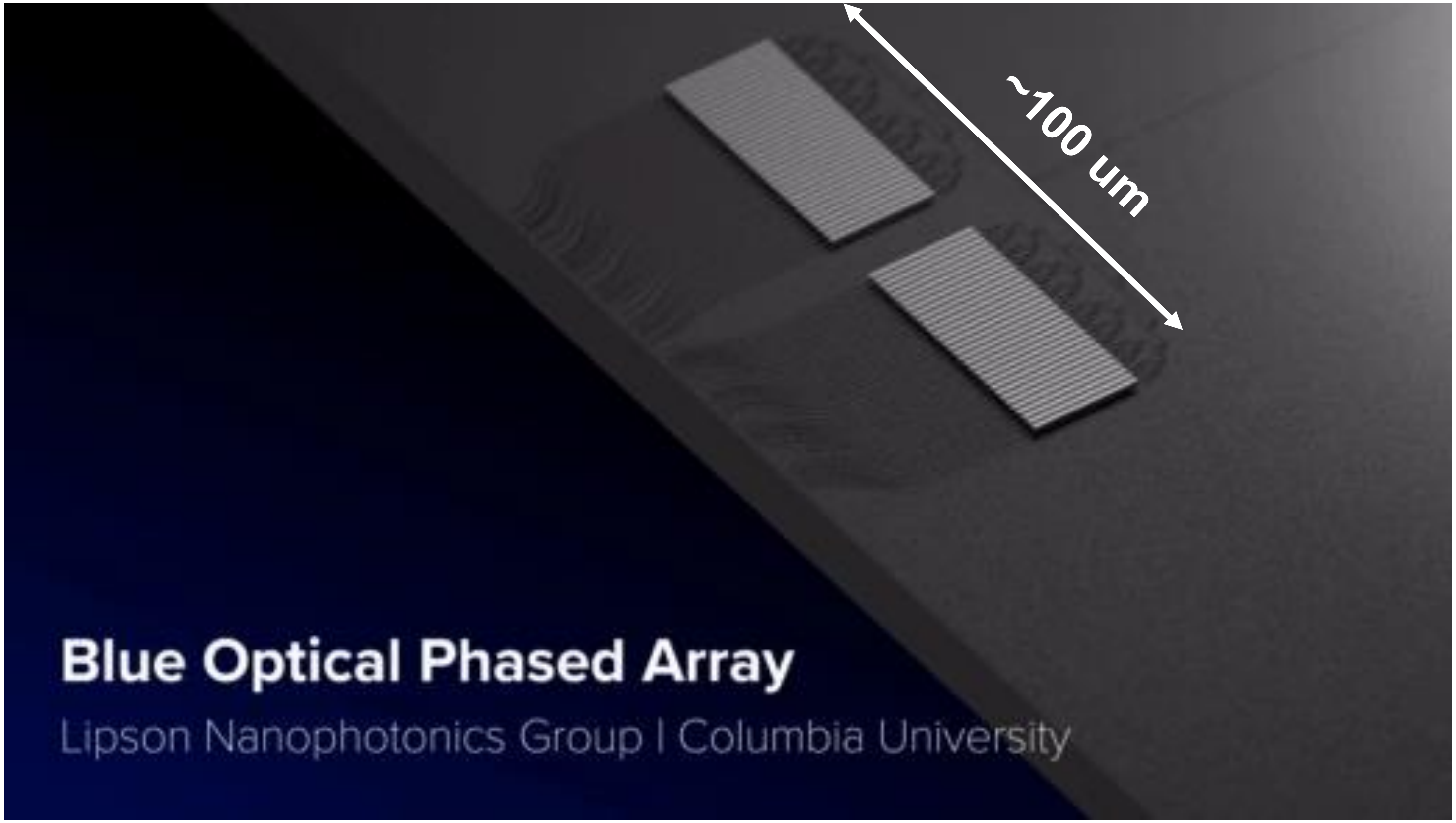
www.phiconference.com

~cm

- **Waveguide avoids diffraction**
- **Waveguide can control dispersions**

Coming back to phased array

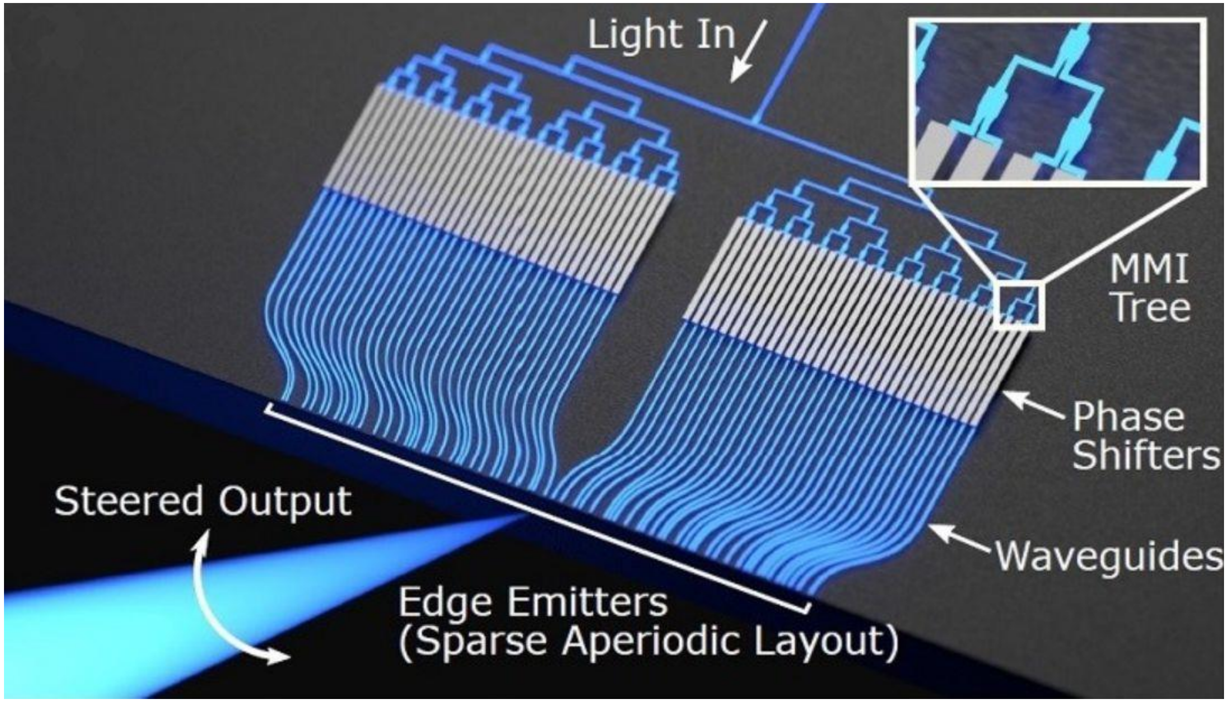
Optical phased array on a PIC



https://www.youtube.com/watch?v=xEqV879qDNE

- **Let's look at it one by one**

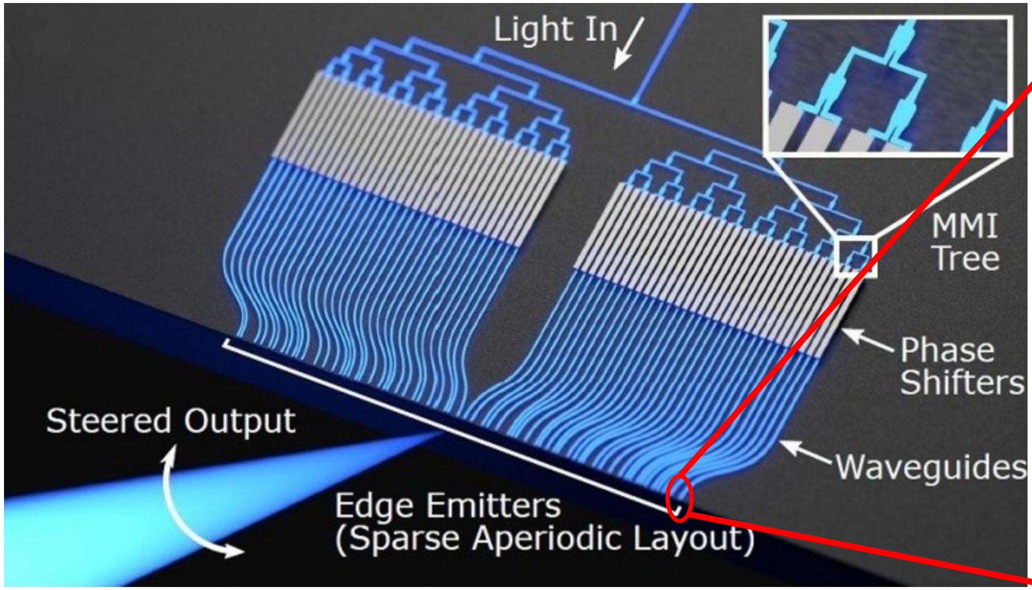
(Passive) Components of PICs

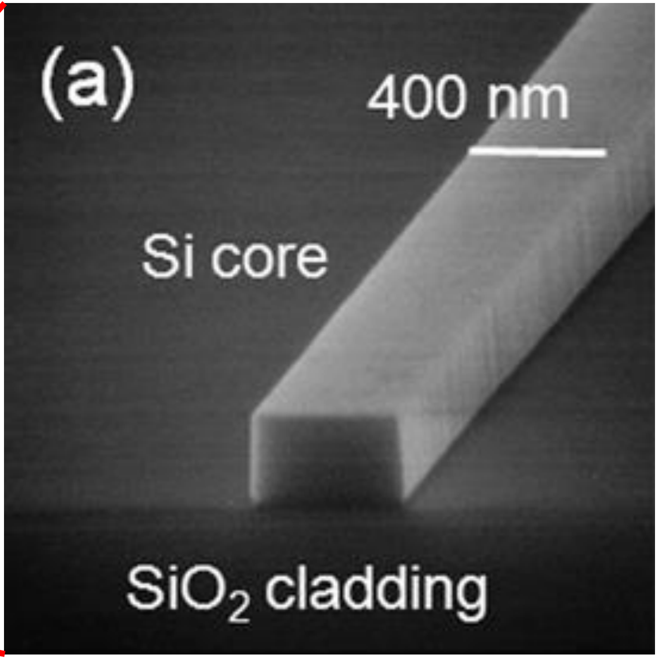


Blue optical phased array for augmented reality, trapped ion quantum computer and optogenetic neural stimulation. Credit: Myles Marshall, Secret Molecule, Min Chul Shin, Aseema Mohanty, Columbia Engineering.

- **Waveguide**
- **Waveguide splitter**
- **Phase shifter (optical path length shifter)**

Waveguide



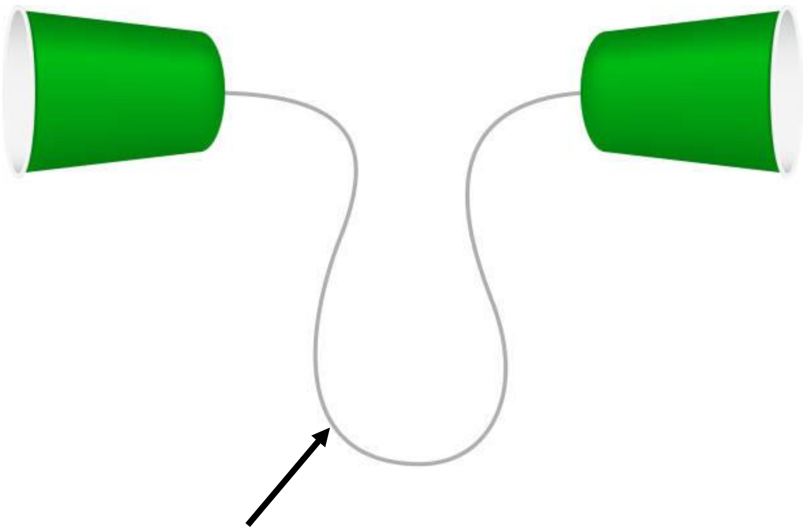


Silicon Photonic Wire Waveguides: Fundamentals and Applications

- **Optical fiber is a good example of waveguide**

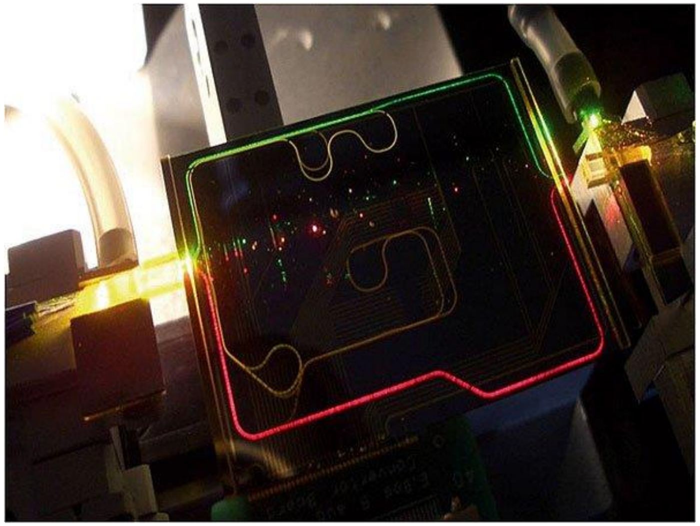
Waveguide

Paper cup telephone



This is (acoustic) waveguide!

Silicon photonic chip

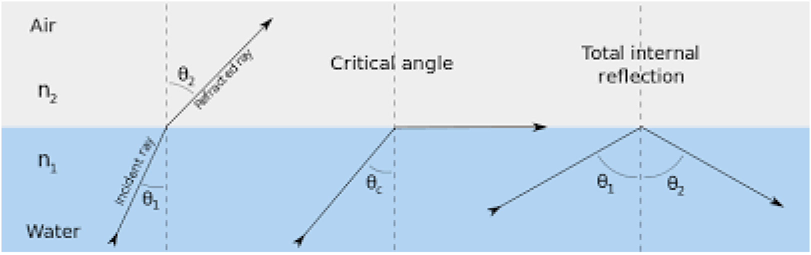


cmmmagazine.com

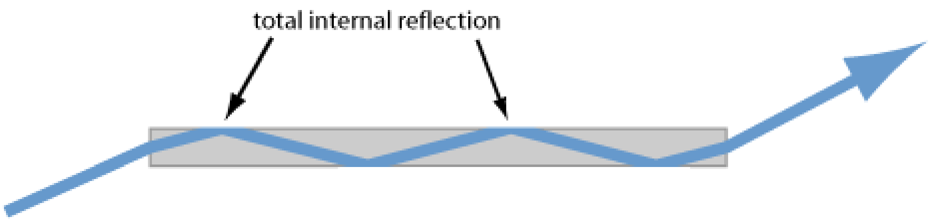
- **Waveguide confine light to prevent dissipation**
- **Controls dispersion, diffraction, etc.**

Light guiding by TIR

Total internal reflection (TIR)



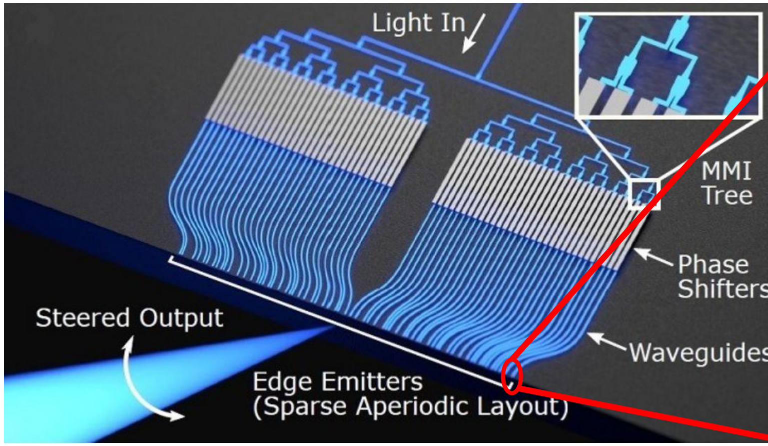
Inside waveguide

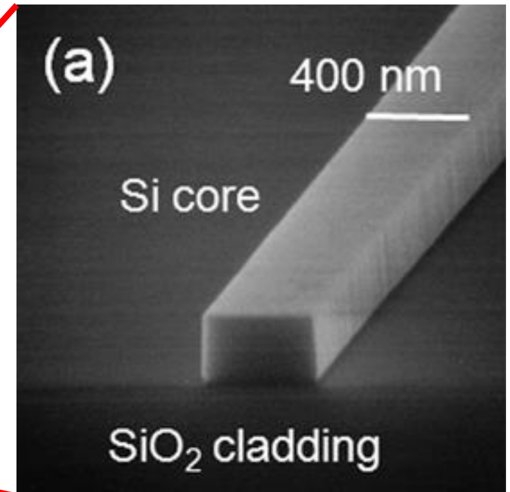


Keerthi, Wikipedia

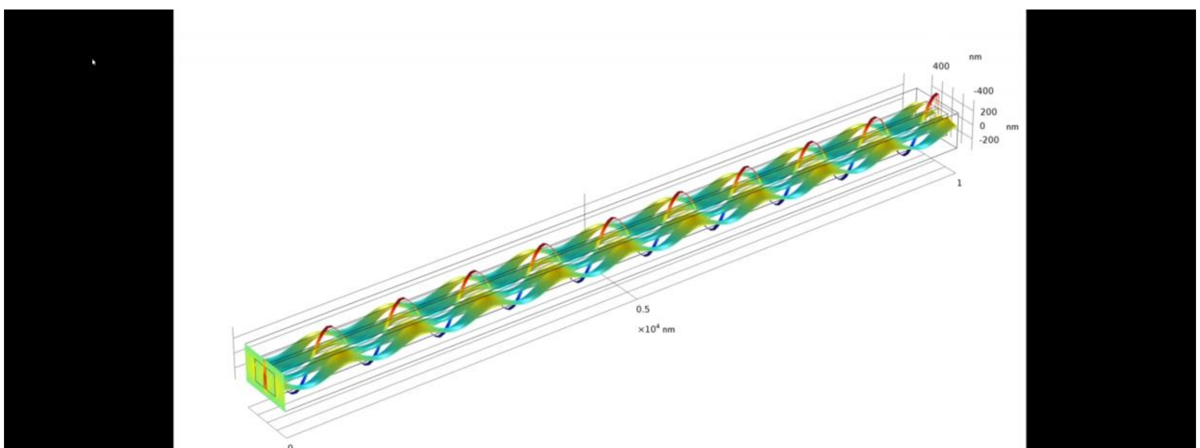
- **Light is guided by TIR**
- **Index contrast is needed**

Waveguide





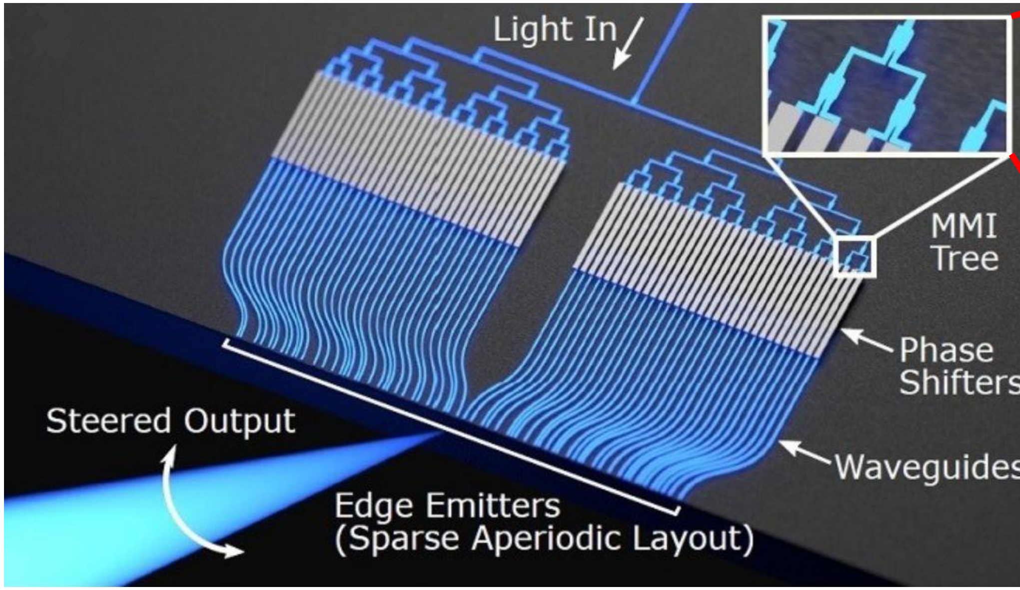
Light propagation in waveguide (~10^{14} x slower video)



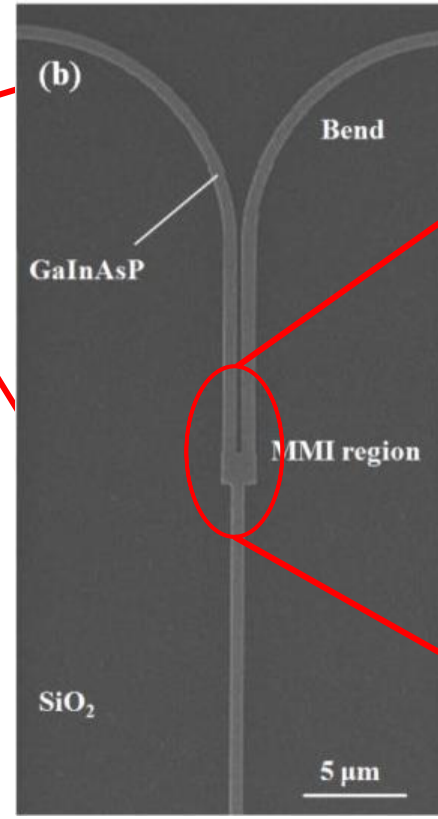
$$E(z,t) = E_0 cos(kz - \omega t + \phi)$$

comsol.com

Waveguide splitter

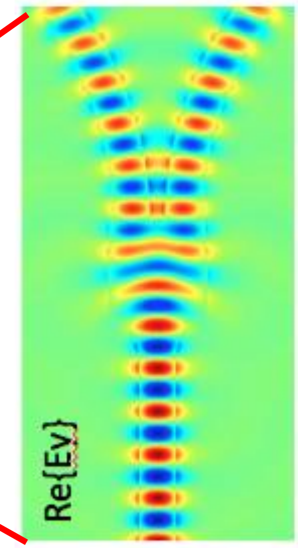


SEM image



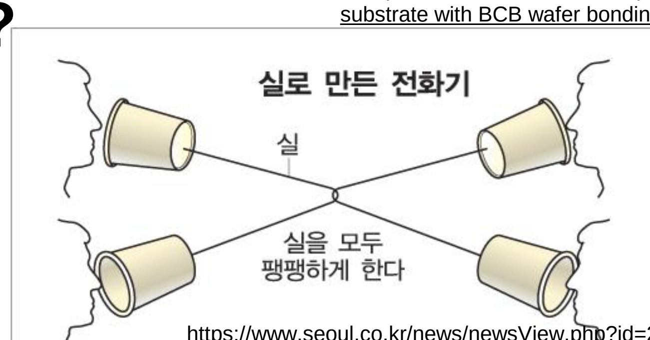
Compact InP-based 1×2 MMI splitter on Si substrate with BCB wafer bonding for membrane

Light propagation



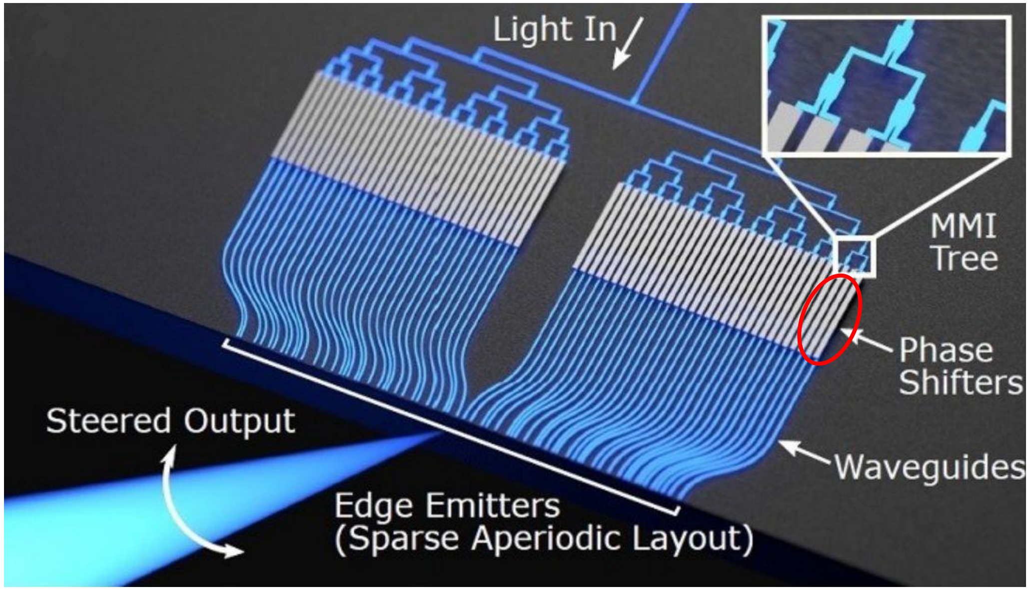
optoelectronics.eecs.berkeley.edu

- **Very intuitive looking?**



https://www.seoul.co.kr/news/newsView.php?id=20060818022003

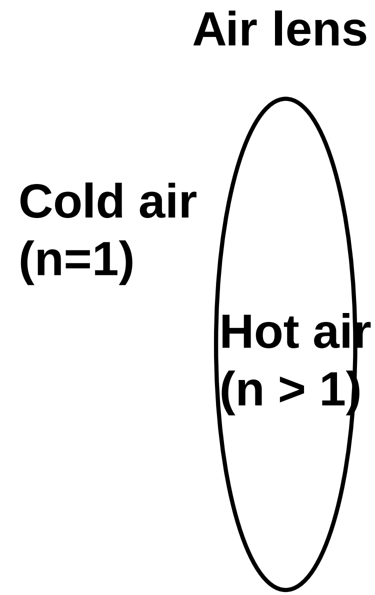
Phase shifter (optical path length shifter)



- Phase shifter = 빛이 느끼는 경로를 조절하는 부품
- 빛이 느끼는 경로 = 실제길이 (L) x 굴절율 (n)
- 물체가 뜨거워지면 n 증가 → 빛이 느끼는 경로 길어짐

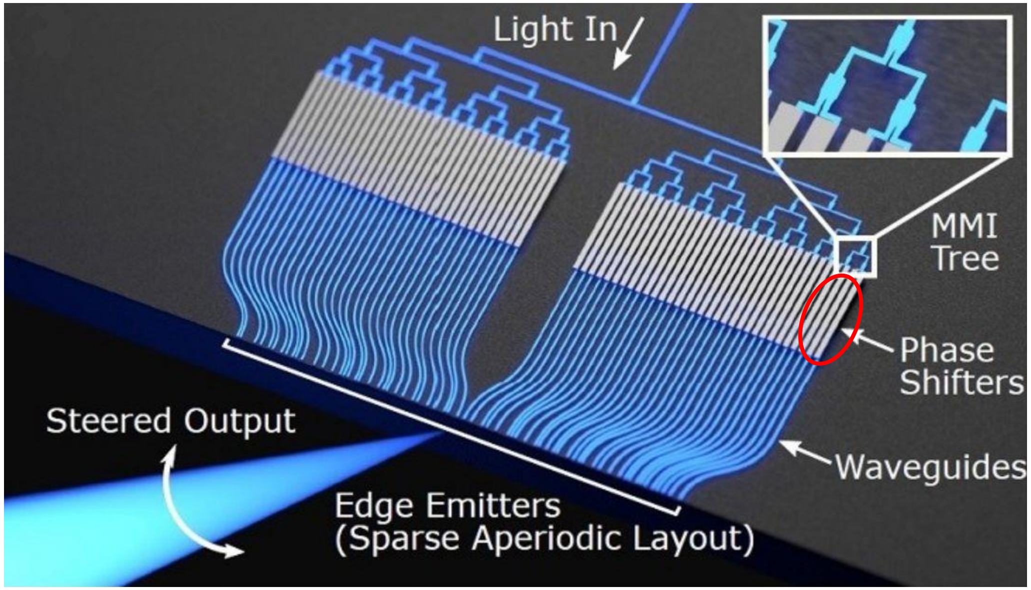
아지랑이 현상

https://www.youtube.com/watch?v=JhGCGNUf3EU

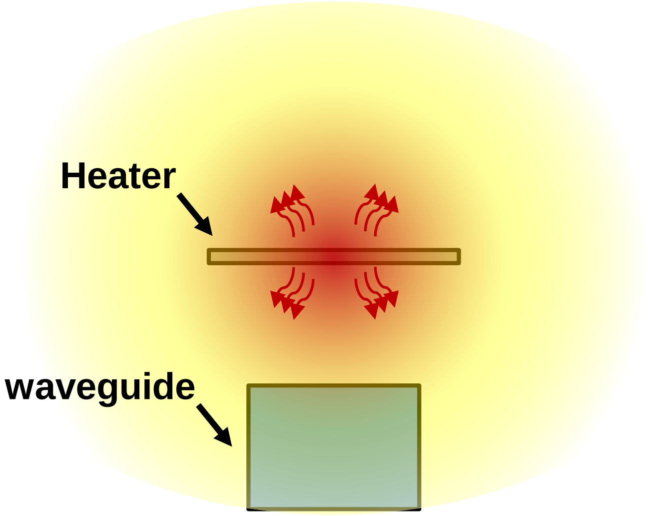


- 공기가 부분부분 뜨겁다 → 곳곳에 작은 렌즈가 있는 효과

Phase shifter (optical path length shifter)

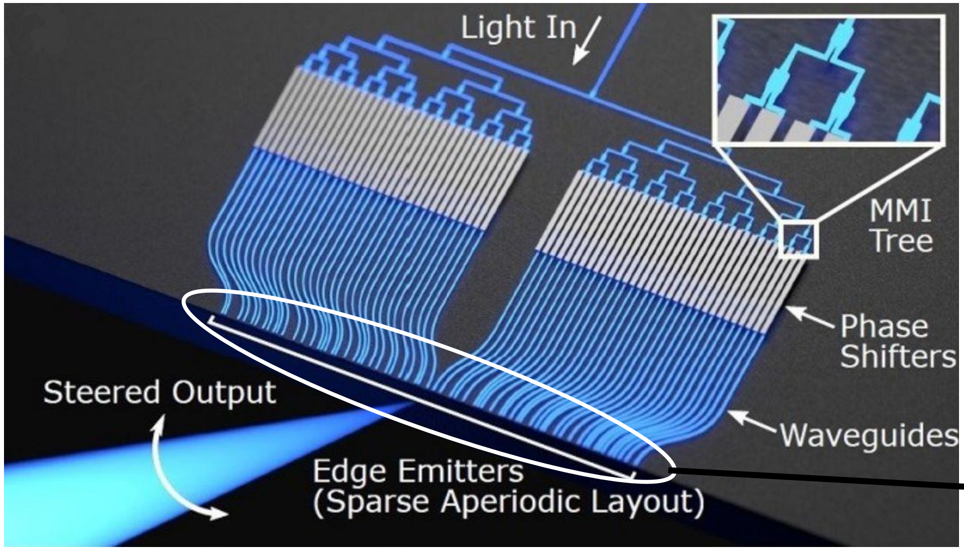


Phase shifter 단면

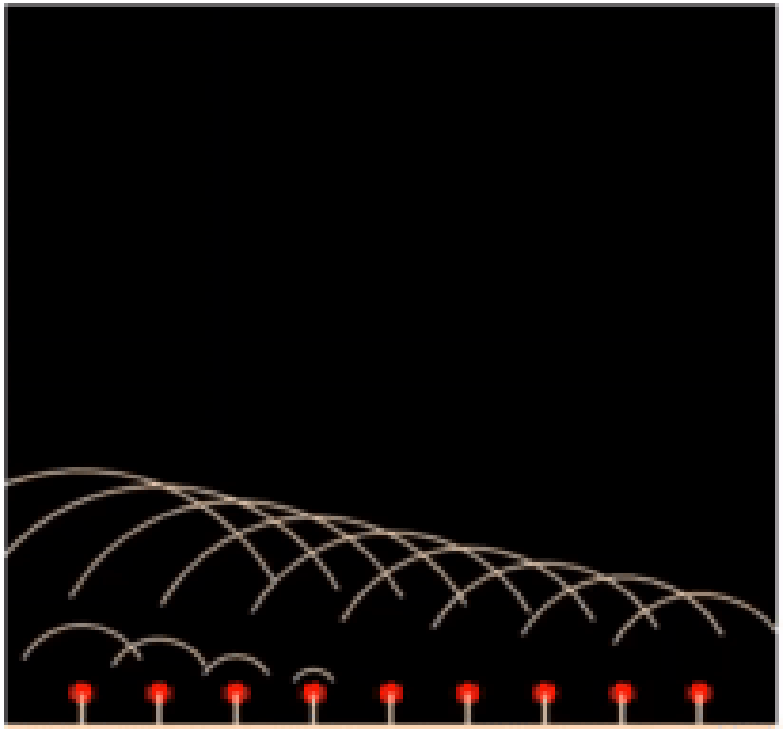


- Phase shifter = 빛이 느끼는 경로를 조절하는 부품
- 빛이 느끼는 경로 = 실제길이 (L) x 굴절율 (n)
- 물체가 뜨거워지면 n 증가 → 빛이 느끼는 경로 길어짐

All together



Blue optical phased array for augmented reality, trapped ion quantum computer and optogenetic neural stimulation. Credit: Myles Marshall, Secret Molecule, Min Chul Shin, Aseema Mohanty, Columbia Engineering.



https://www.youtube.com/watch?v=vLmhzv_T-74

Photonics for Intelligence
-Lecture 3:
Photonic hardware accelerators-

Prof. Sangyoon Han

DGIST class material

Spring 2021

Background image: silicon photonic switch fabricated by Prof. Sangyoon Han

Computing with light

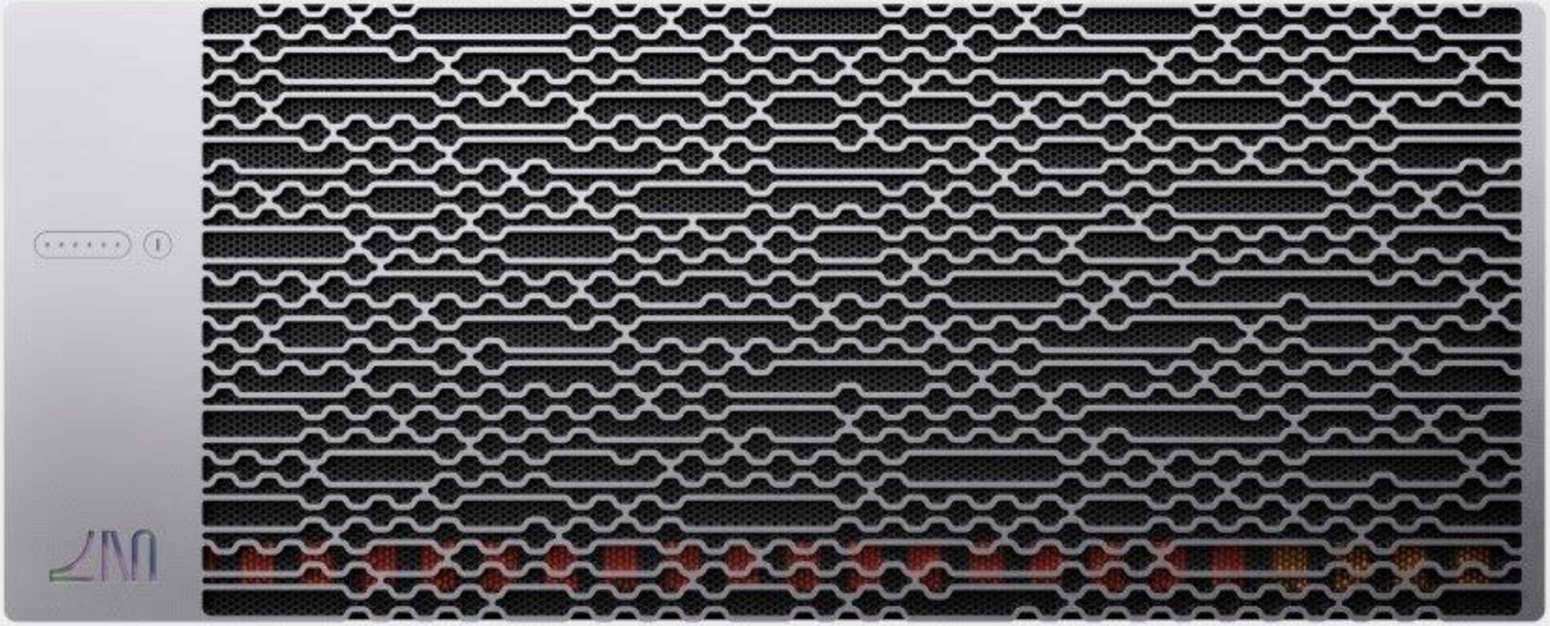
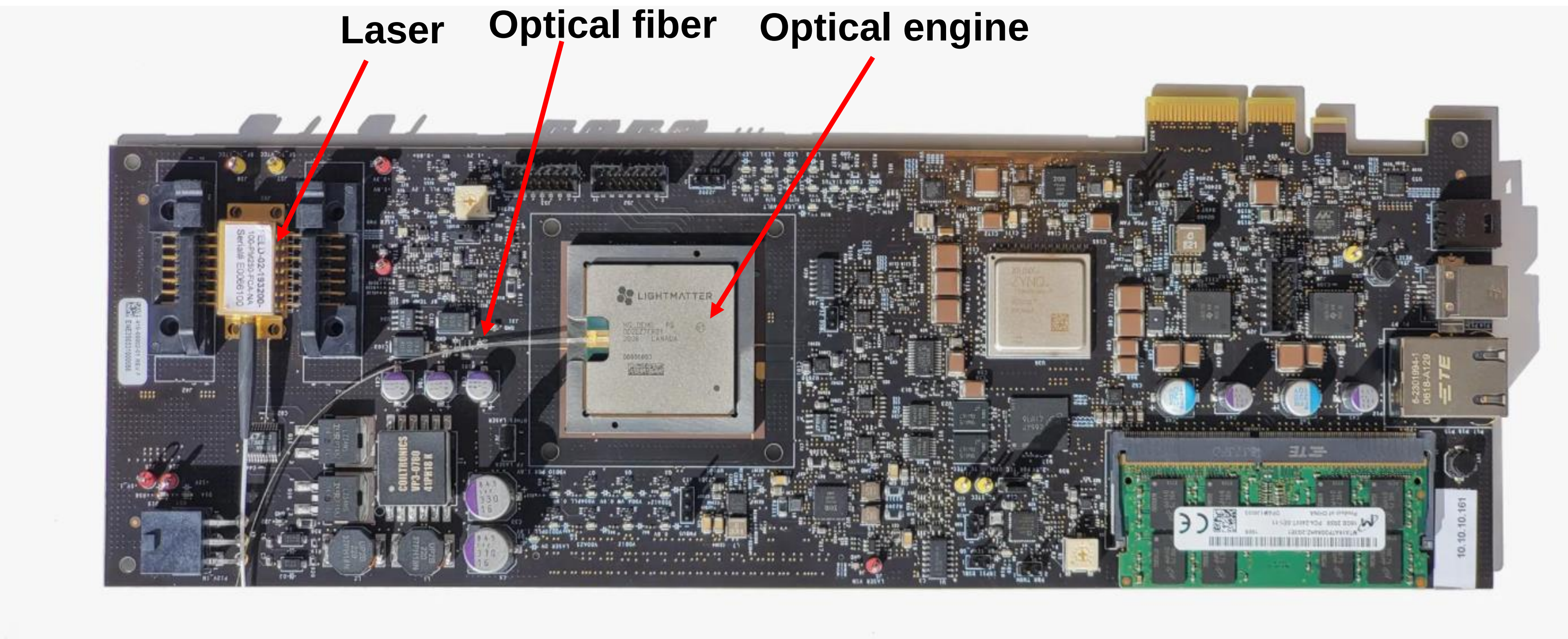


Image Credits: Lightmatter

WILL KNIGHT BUSINESS 03.10.2021 07:00 AM

This Chip for AI Works Using Light, Not Electrons

Lightmatter says the computing and power demands of complex neural networks need new technologies like these to keep up.

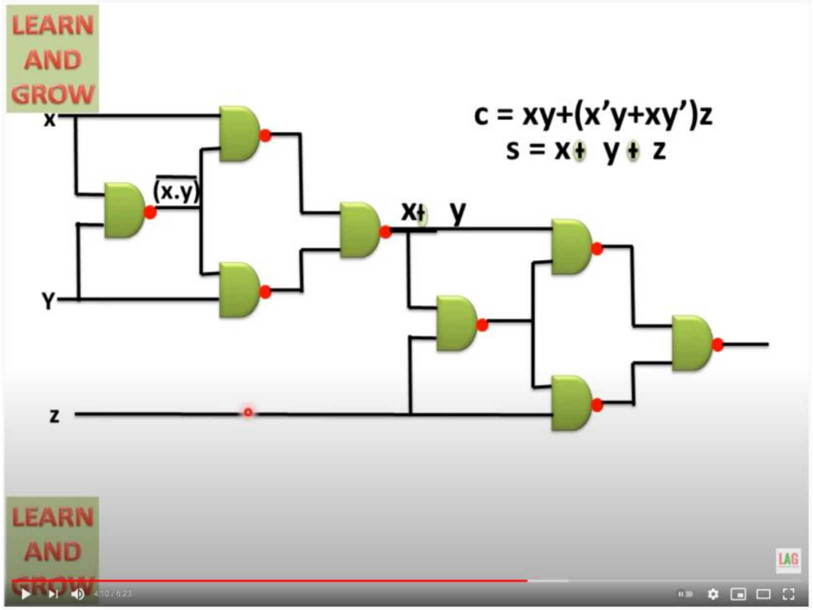


Computation

Electronic computer example

A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

http://hyperphysics.phy-astr.gsu.edu/hbase/Electronic/nand.html



https://www.youtube.com/watch?v=N-fBJyQr8Uo

- **One can do any calculation with one gate (NAND)**
- **그냥 내가 암산하는게 더 빠르지 않을까…….**

What if you have 10^{10} of them??

Transistor
(electronic switch)

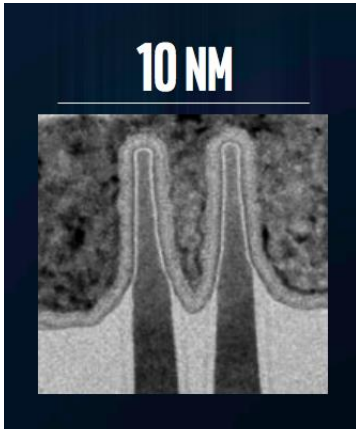
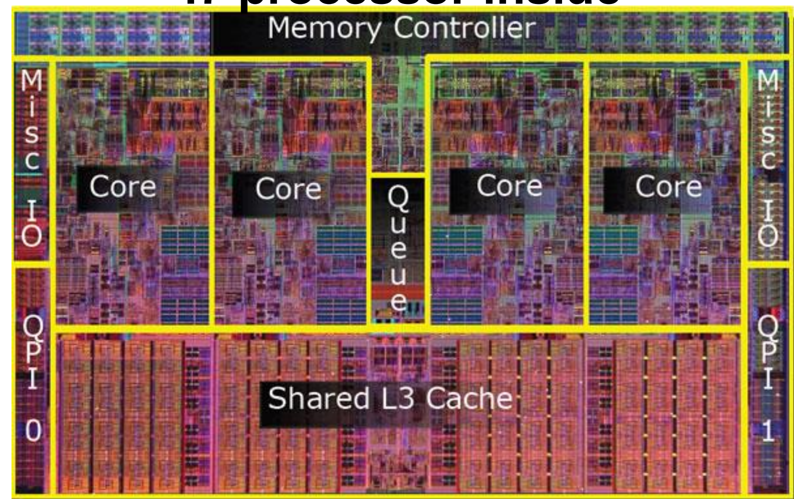


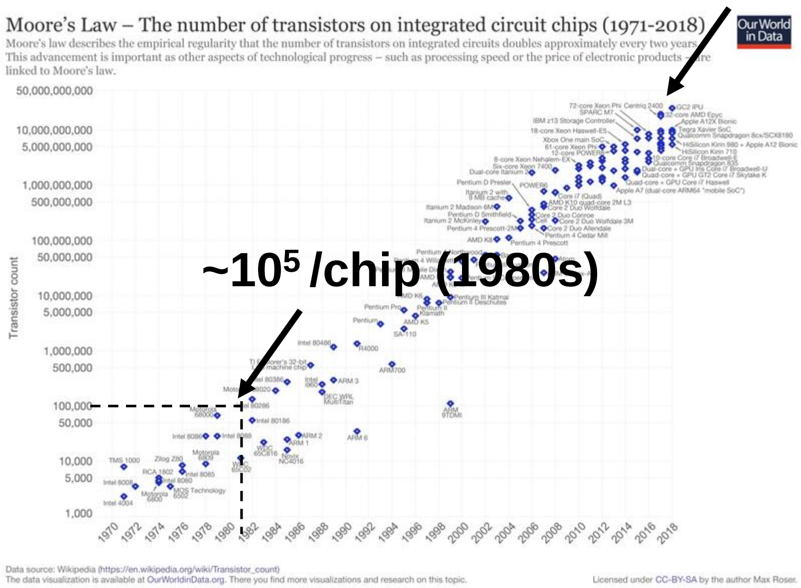
Image: Intel

i7 processor inside



https://pcper.com/2008/11/nehalem-revolution-intels-core-i7-processor-complete-review/

~10^{10} /chip



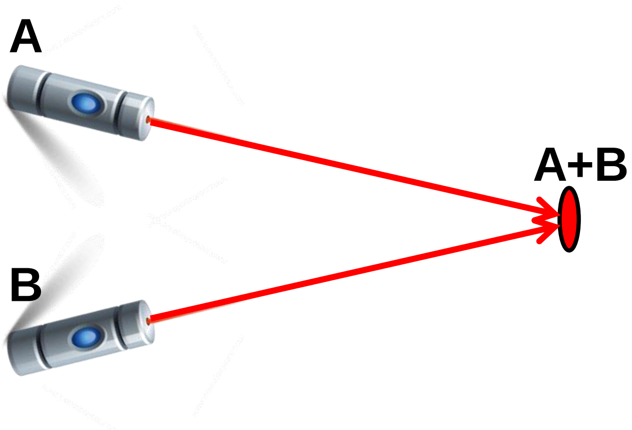
~10^5 /chip (1980s)

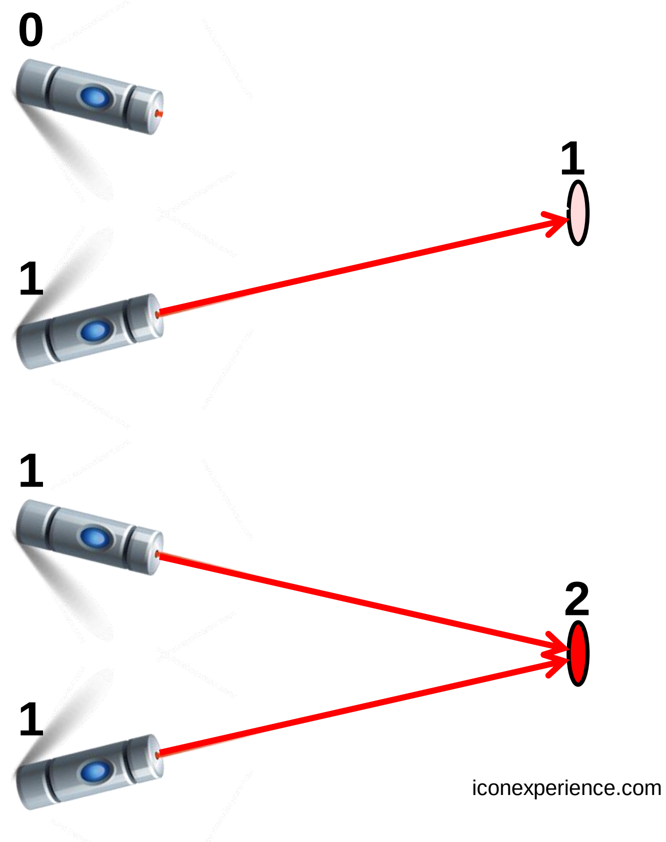
ourworldindata.org

- **They work at 3 GHz**
  - **$3*10^9$ operation per second**
- **$7*10^9$ people in the world**

Calculation using light

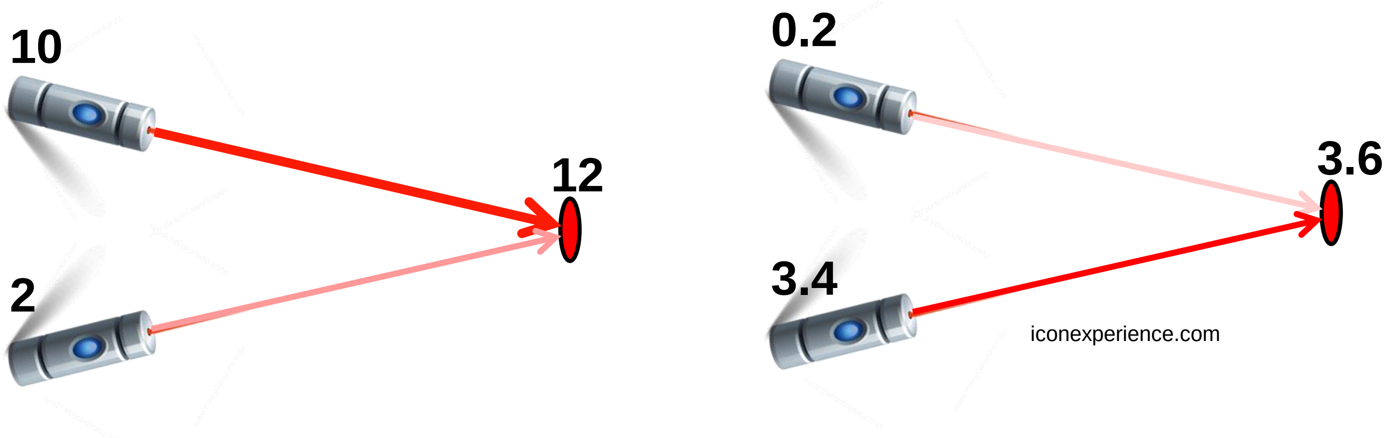
Addition (A+B)





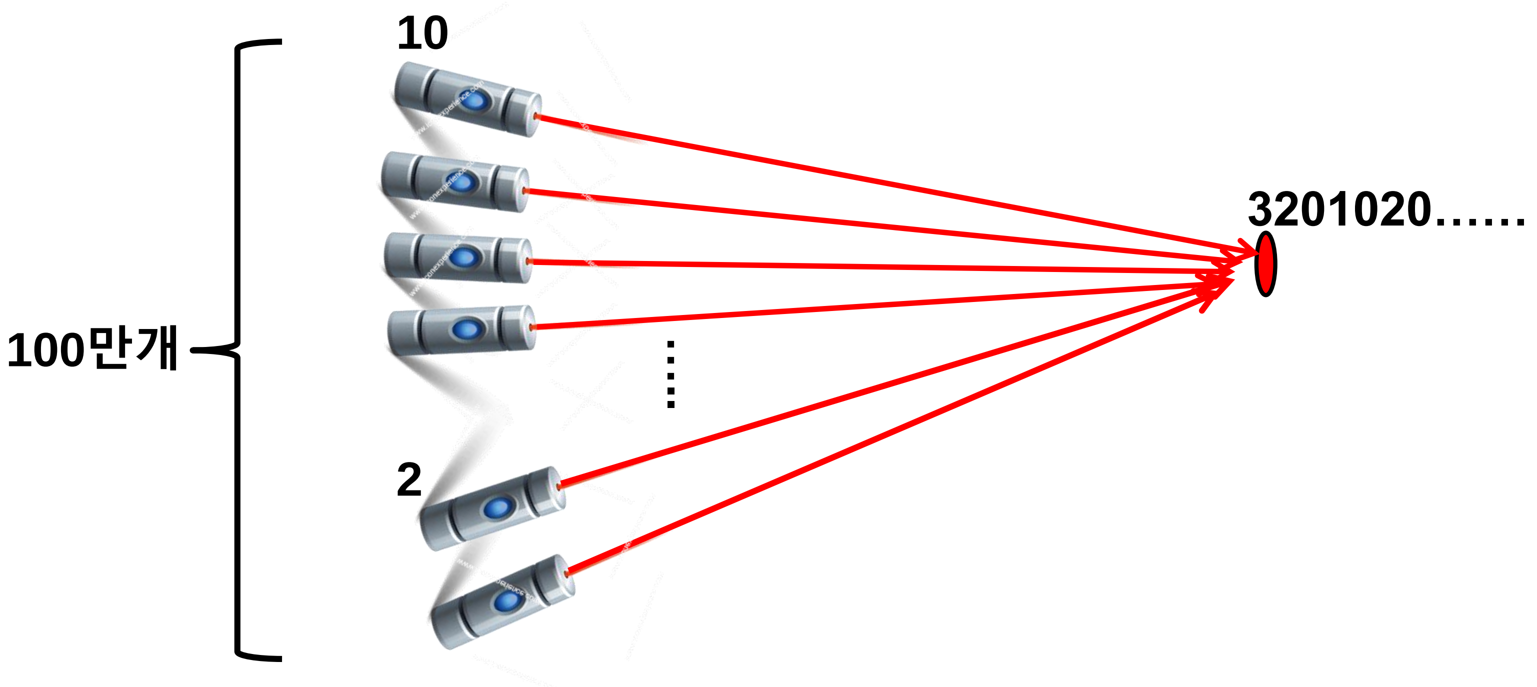
- 그, 그래....
- 그냥 내가 암산 할게.....

Calculation using light



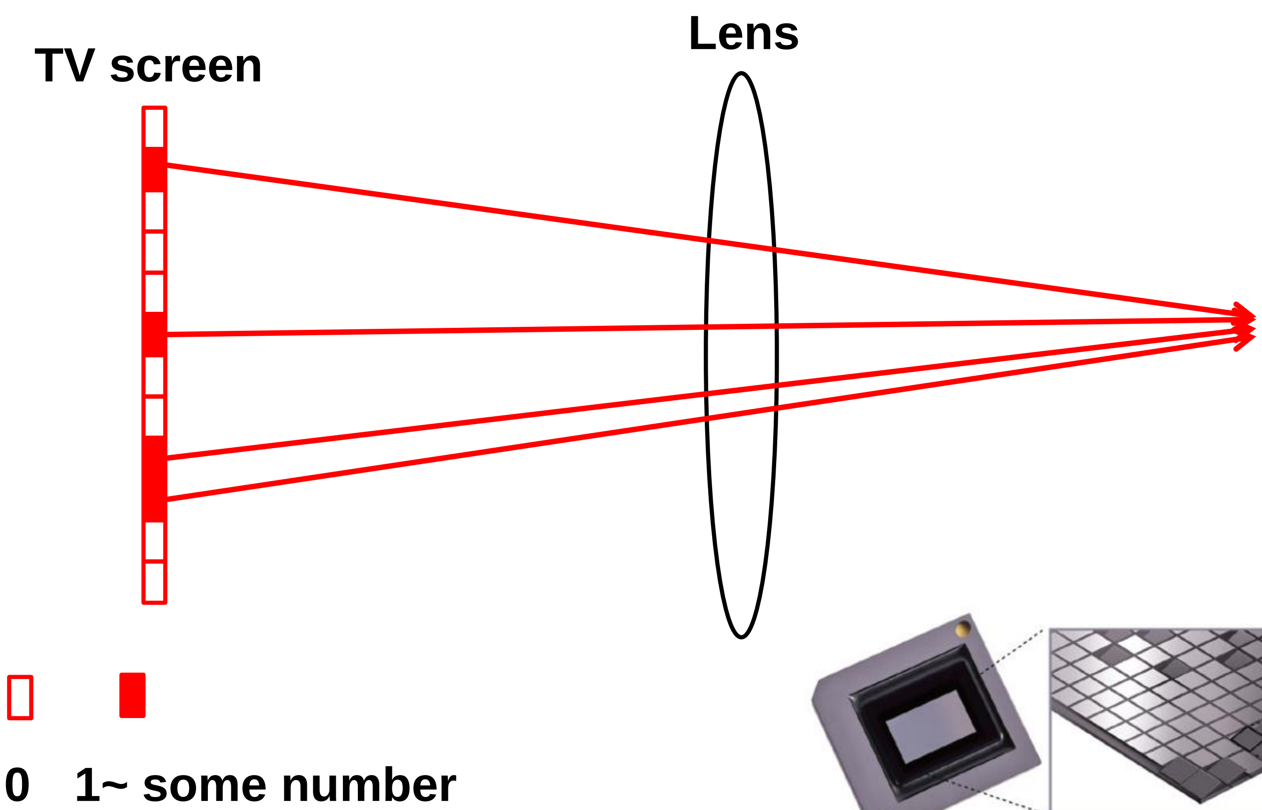
- 어, 나보다 나을수도 (?!)

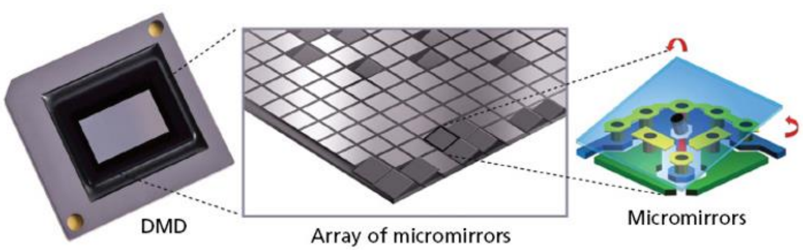
Calculation using light



- 어, 나보다 확실히 나아….
- 그런데, 100만개 어떻게 만들거야???

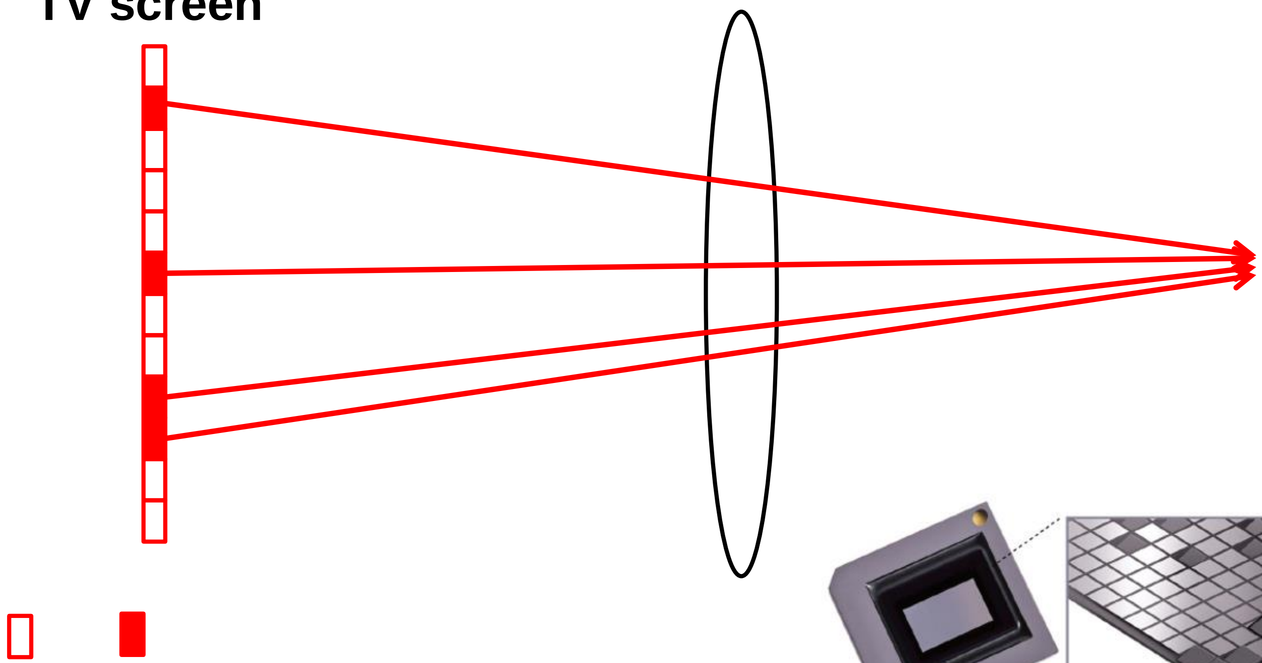
Calculation using light



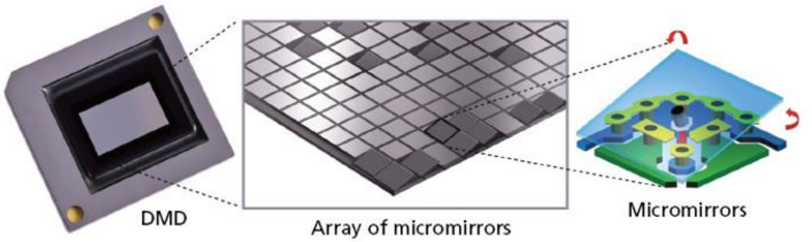


- We have displays (e.g. TV) (~2000x1000) and lenses
- How long does it take to do the calculation?

How long does it take to do the calculation?

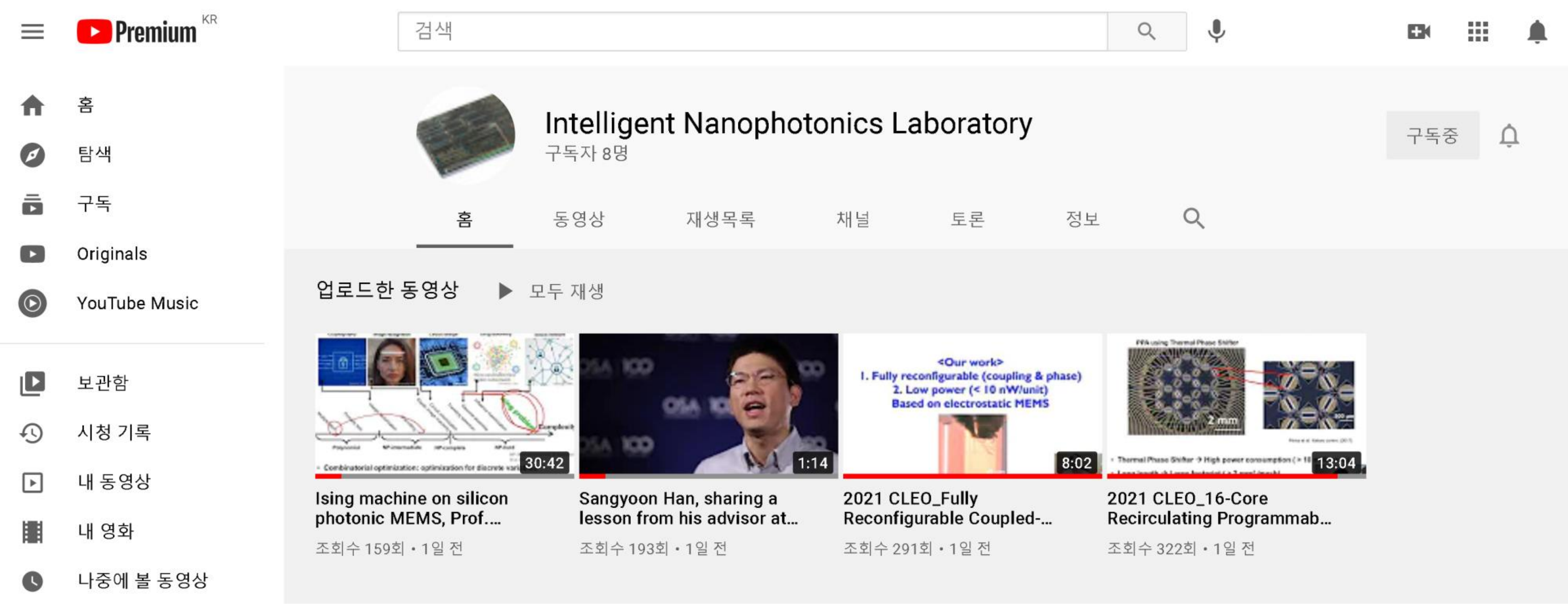


0 1~ some number



- Time takes for calculation: 3.3×10^{-10}s ($= \frac{10\ cm}{speed\ of\ light}$)
- 100만번의 덧셈을 3×10^{-10}초 만에 완수
- 전자식 컴퓨터는? (한 clock 당 덧셈을 한번 한다고 하면)
  - $\frac{1}{3GHz} * 100만 = 3.3 \times 10^{-4} s$
- 빛으로 하면 약 100 만배 빠르게 가능하다 (fundamentally)

연구실 유튜브 채널 개설!
(Intelligent Nanophotonics Laboratory)

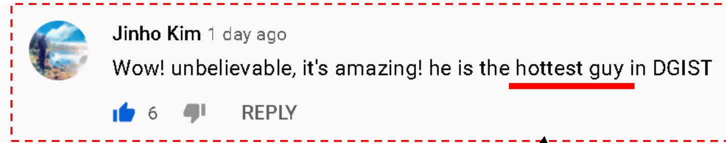


- **채널 주소: https://www.youtube.com/channel/UC9xRW1kJITc1s1BsiSC_b7A**
- **연구실에서 진행되는 연구 관련 동영상 업로드**
- **연구실 홈페이지 주소: https://www.intelligent-photonics.com/**

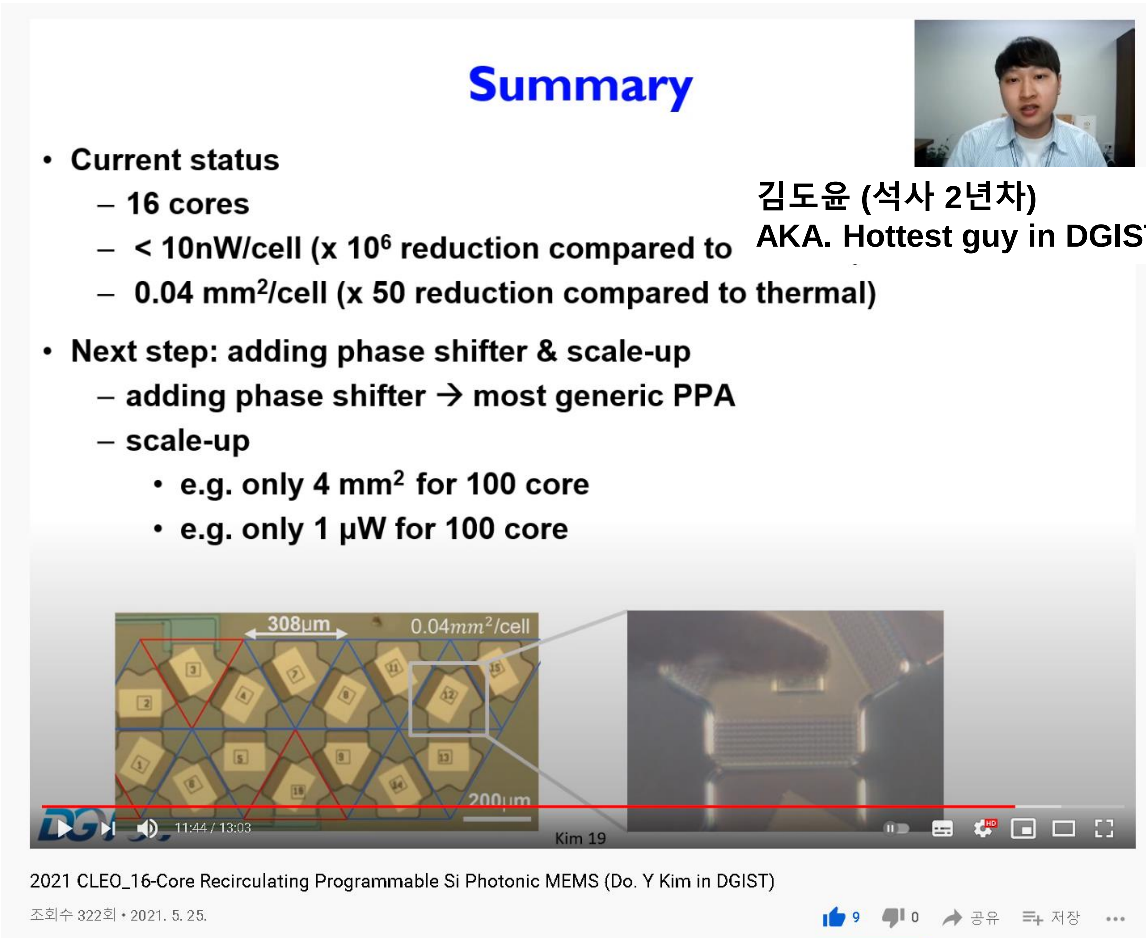
학생분들 (및 교수) 댓글 놀이 중

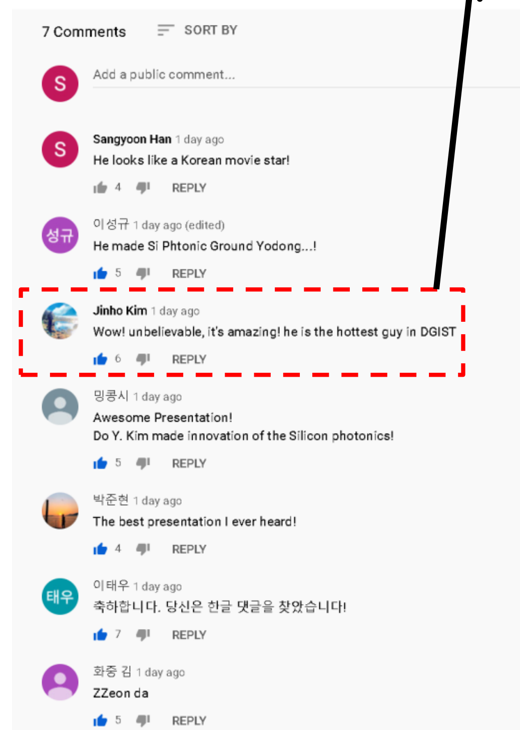
이재홍 교수님 연구실 김진호 학생 (키 183 의 남자)

베댓



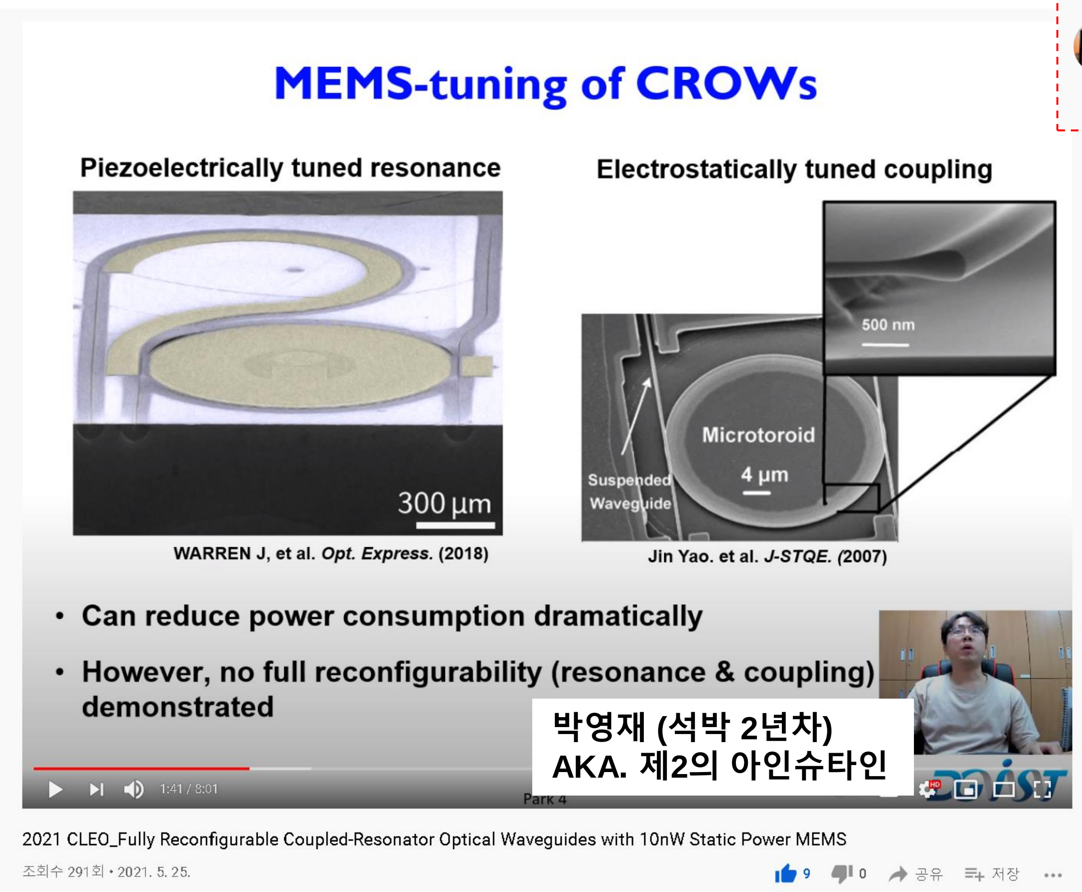
김도윤 (석사 2년차)
AKA. Hottest guy in DGIST





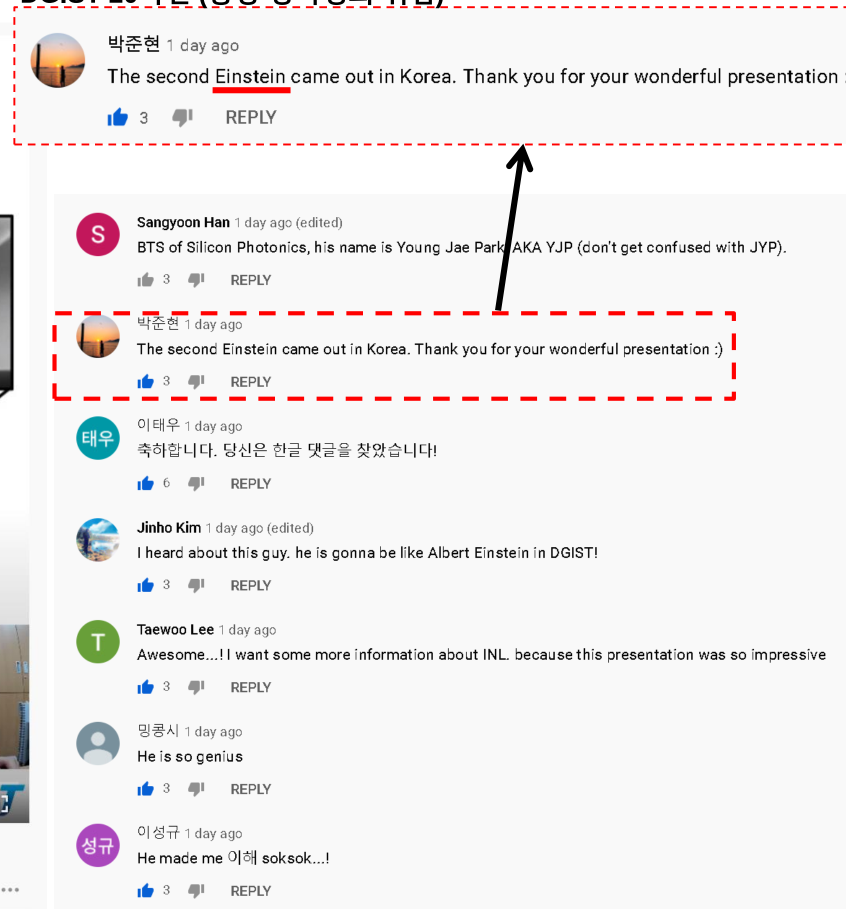
- 아무말 대잔치: 욕만 아니면 와서 아무말이나 써도 됩니다!

학생분들 (및 교수) 댓글 놀이 중



DGIST 20학번 (총장 장학생의 위엄)

베댓

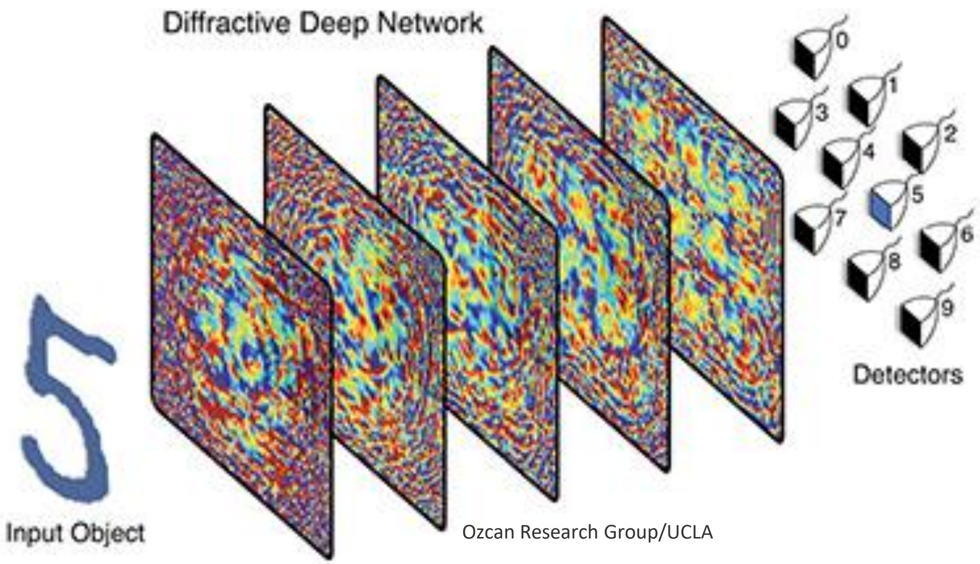


- 아무말 대잔치: 욕만 아니면 와서 아무말이나 써도 됩니다!

Optical neural network

Optical deep neural networks

Optical neural net



Ozcan Research Group/UCLA

RESEARCH

OPTICAL COMPUTING

All-optical machine learning using diffractive deep neural networks

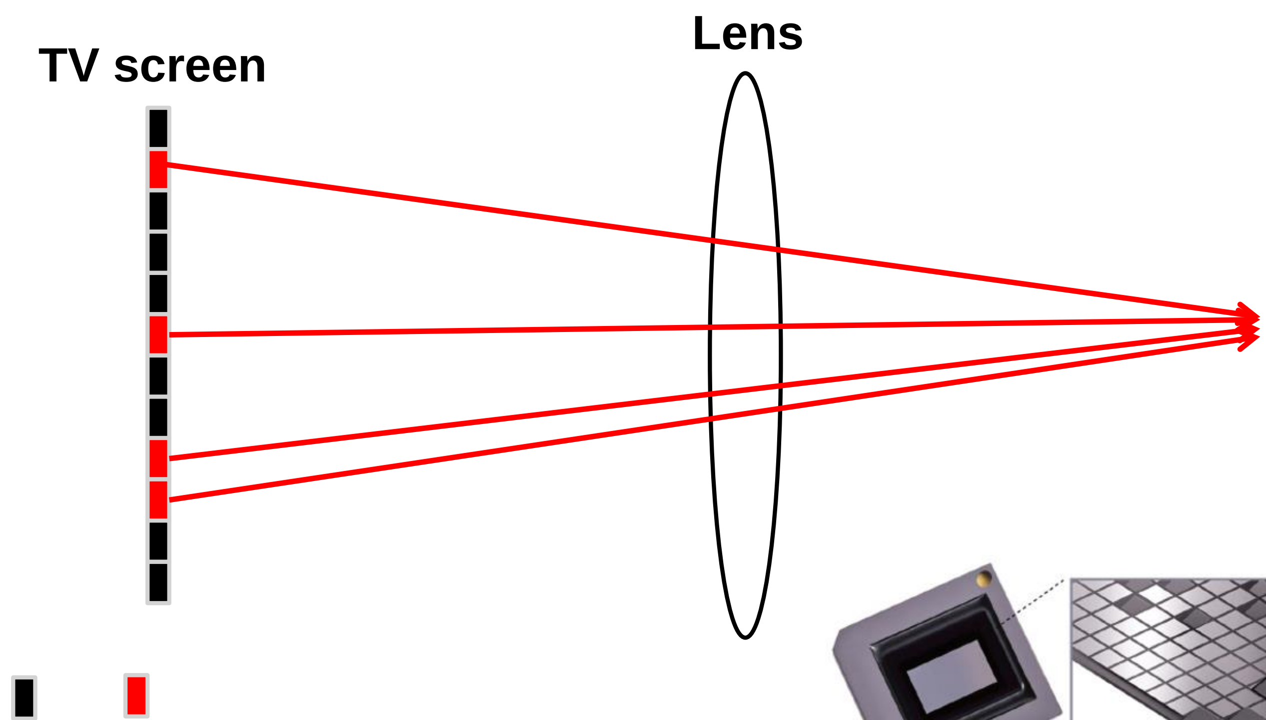
Xing Lin[1,2,3]*, Yair Rivenson[1,2,3]*, Nezih T. Yardimci[1,3], Muhammed Veli[1,2,3], Yi Luo[1,2,3], Mona Jarrahi[1,3], Aydogan Ozcan[1,2,3,4]†

Deep learning has been transforming our ability to execute advanced inference tasks using computers. Here we introduce a physical mechanism to perform machine learning by demonstrating an all-optical diffractive deep neural network (D^2NN) architecture that can implement various functions following the deep learning–based design of passive diffractive layers that work collectively. We created 3D-printed D^2NNs that implement classification of images of handwritten digits and fashion products, as well as the function of an imaging lens at a terahertz spectrum. Our all-optical deep learning framework can perform, at the speed of light, various complex functions that computer-based neural networks can execute; will find applications in all-optical image analysis, feature detection, and object classification; and will also enable new camera designs and optical components that perform distinctive tasks using D^2NNs.

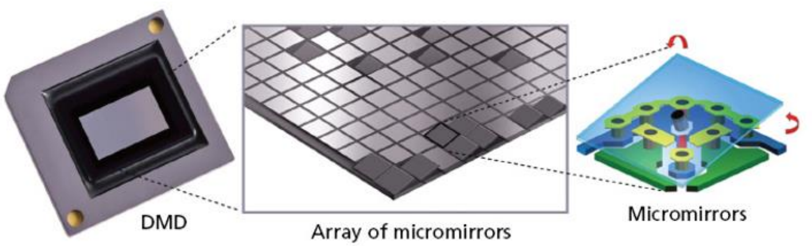
Science 2018

Vector-matrix multiplication using lens (렌즈를 이용한 벡터-행렬 곱셈)

Computation using lens

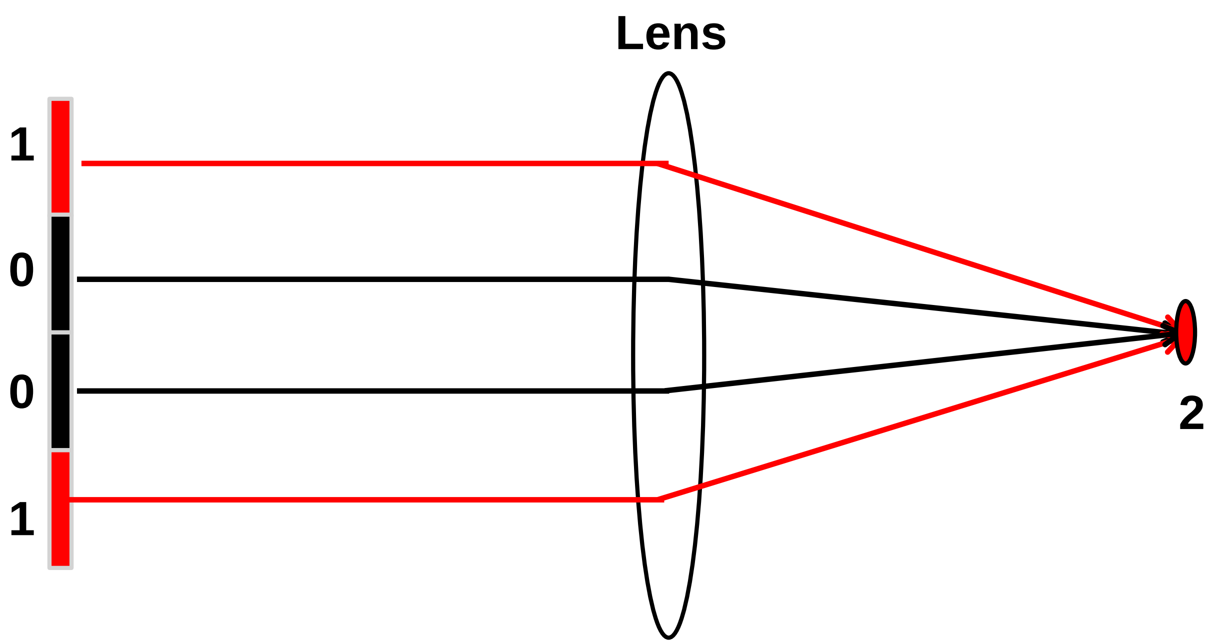


0 1~ some number

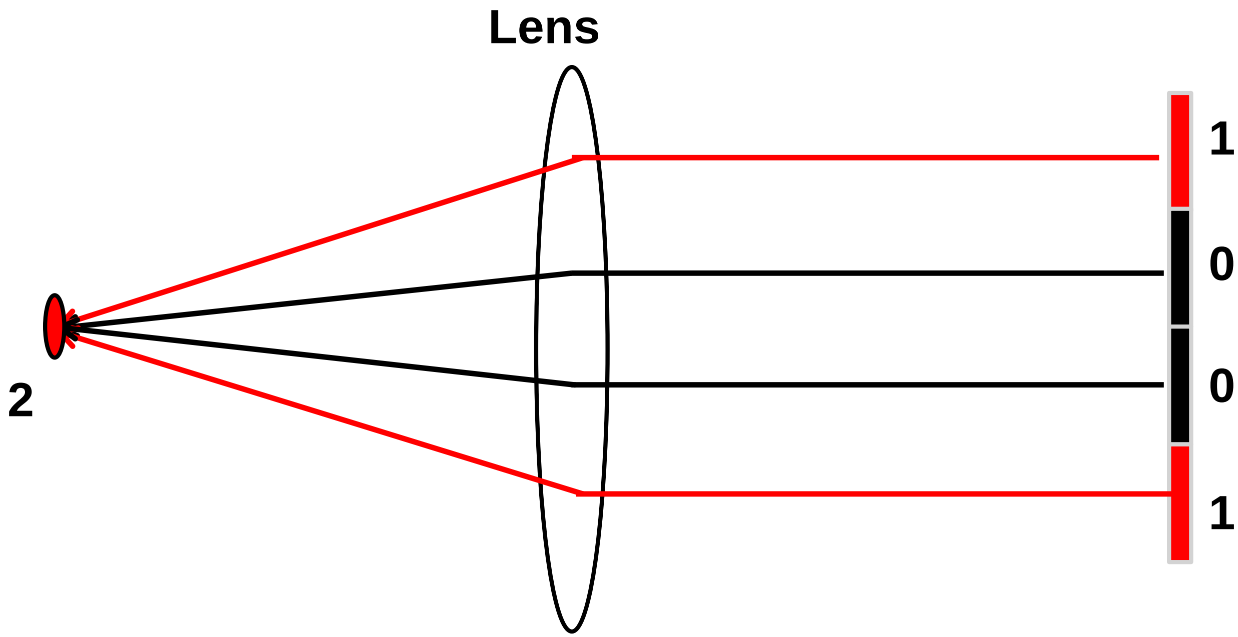


- Time takes for calculation: $3.3\text{x}10^{-10}$s ($= \frac{10\ cm}{speed\ of\ light}$)
- 100만번의 덧셈을 $3\text{x}10^{-10}$초 만에 완수
- 전자식 컴퓨터는? (한 clock 당 덧셈을 한번 한다고 하면)
  - $\frac{1}{3GHz} * 100\text{만} = 3.3 \times 10^{-4} s$
- 빛으로 하면 약 100 만배 빠르게 가능하다 (fundamentally)

얘네가 지금 무슨 짓을 하고 있는 걸까요??

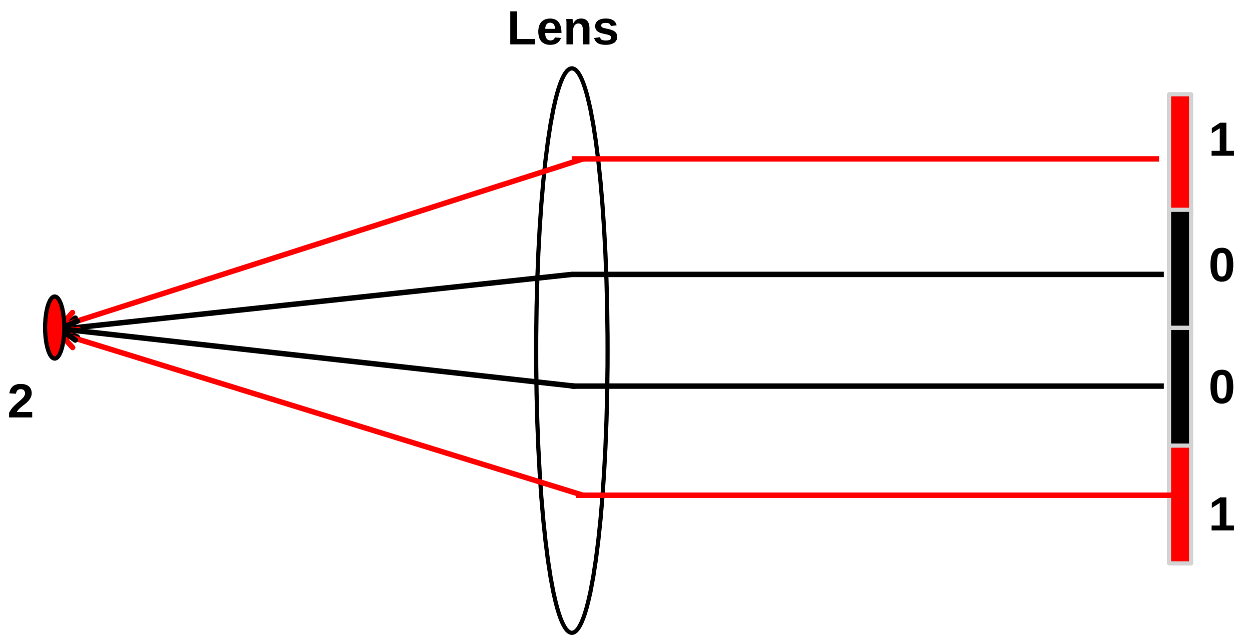


얘네가 지금 무슨 짓을 하고 있는 걸까요??



- 좌우를 뒤집어서 보겠습니다.
- 알 것 같나요??

Vector-matrix multiplication using lenses



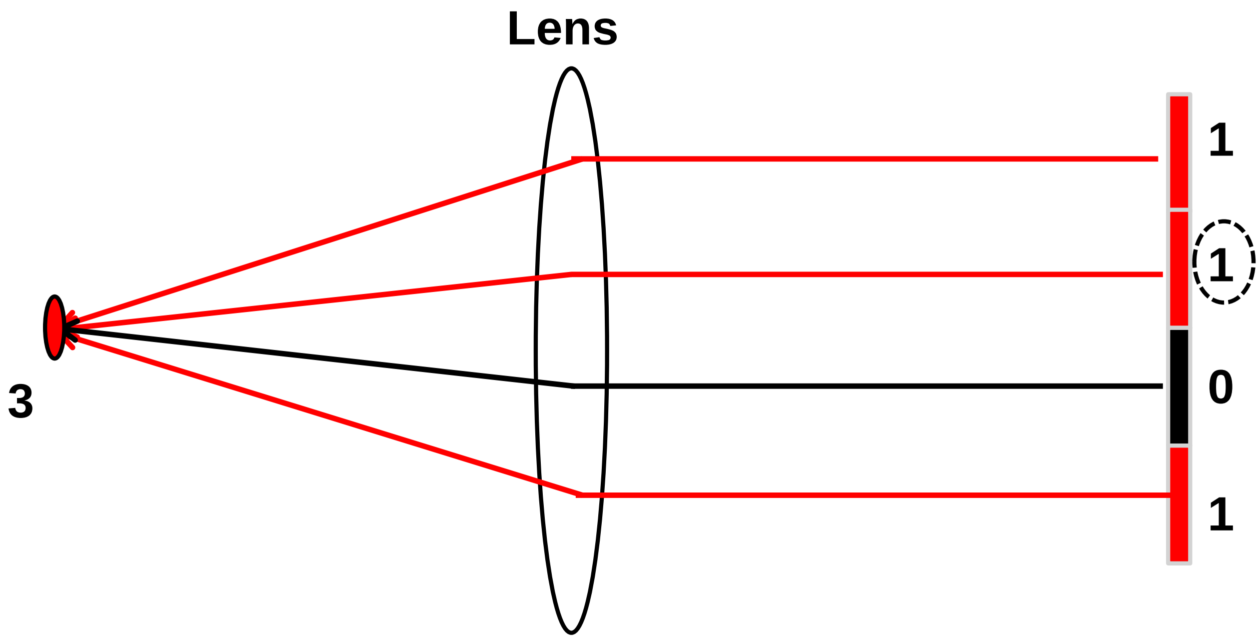
4차 벡터

$$2 = [1\ 1\ 1\ 1] \times \begin{bmatrix}1\\0\\0\\1\end{bmatrix}$$

1x4 행렬

- 행렬-벡터 곱셈을 하고 이따!
- 4차 벡터에 1x4 행렬을 곱해따!

Vector-matrix multiplication using lenses



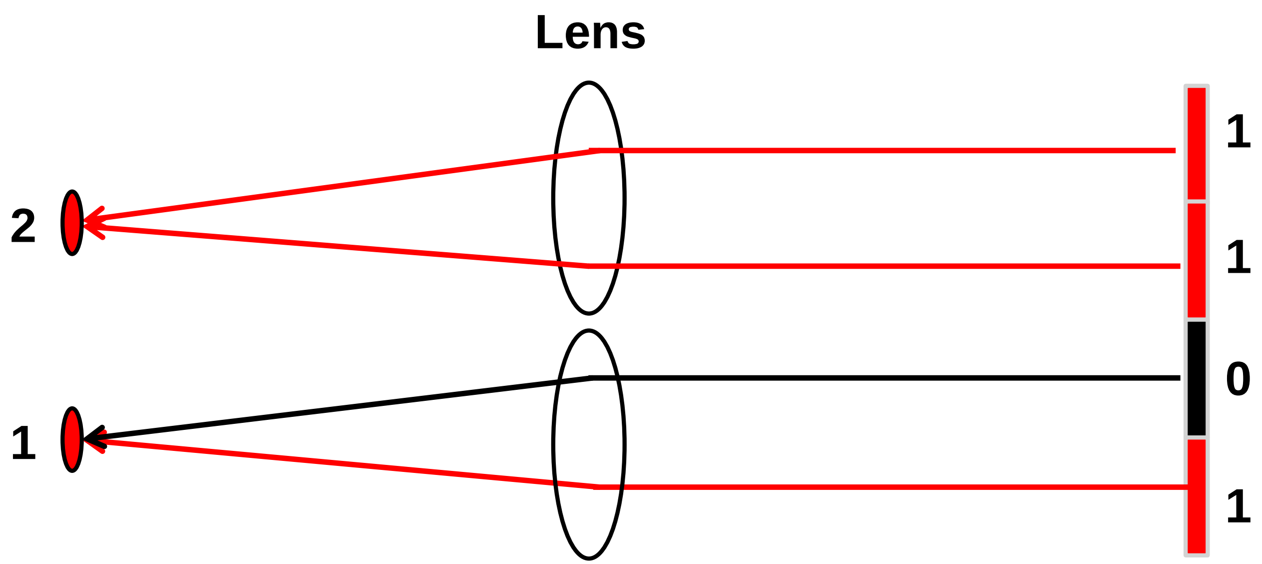
4차 벡터

$$3 = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

1x4 행렬

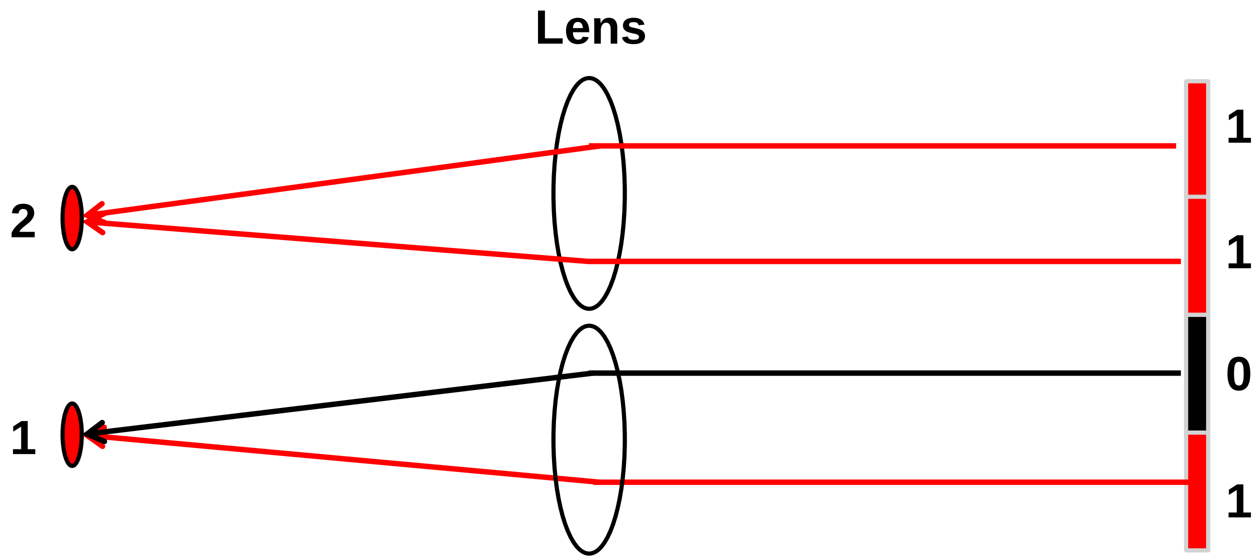
- 정말 곱셈 중이군....
- 좀 더 복잡한 계산 해볼까?

Two lens system



- 그럼 이건 어떤 계산을 하고 있는 걸까요?

Two lens system



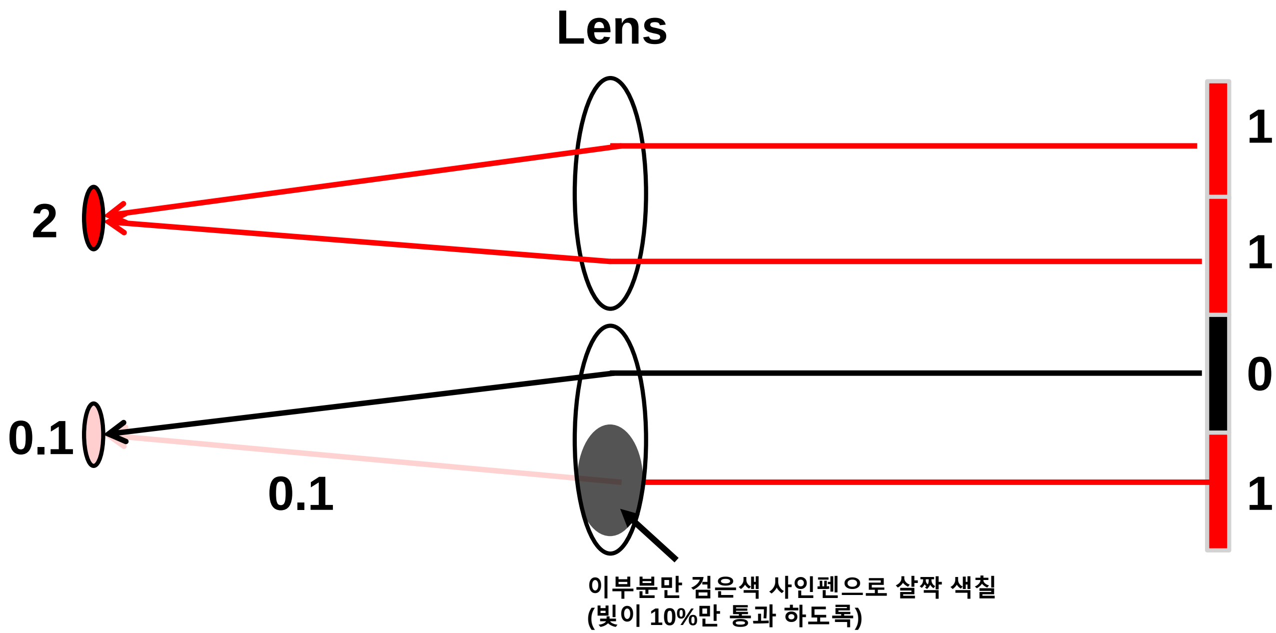
$$\begin{bmatrix} 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

2차 벡터

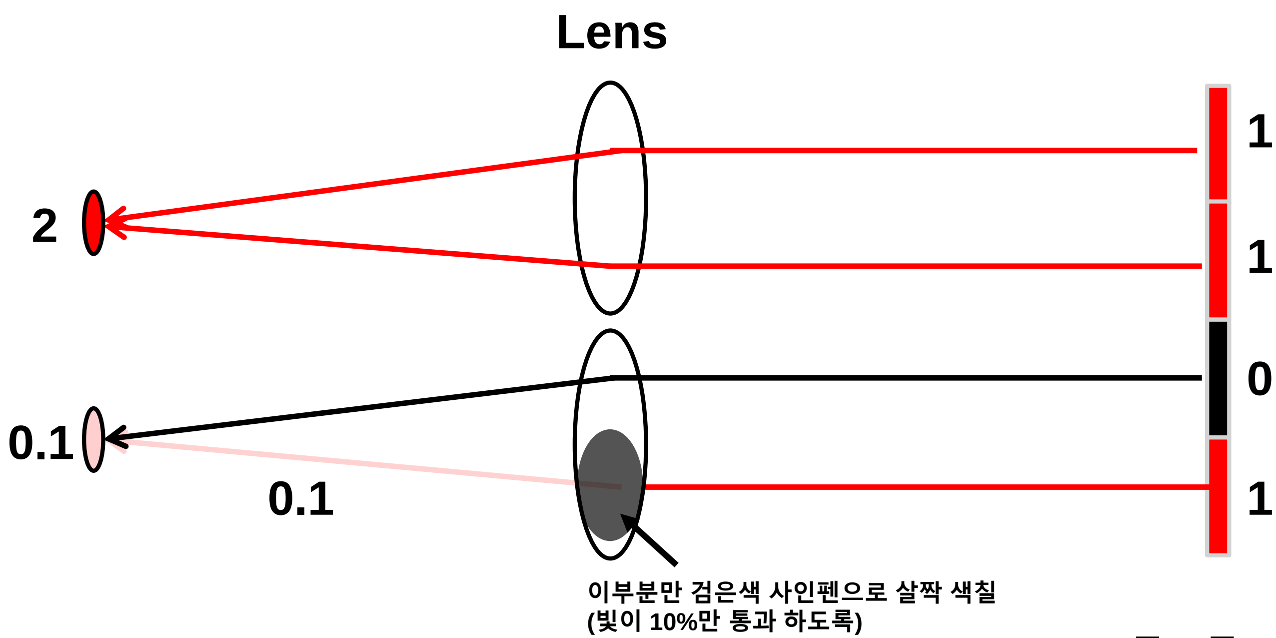
2x4 행렬

4차 벡터

그럼 이건?



그럼 이건?

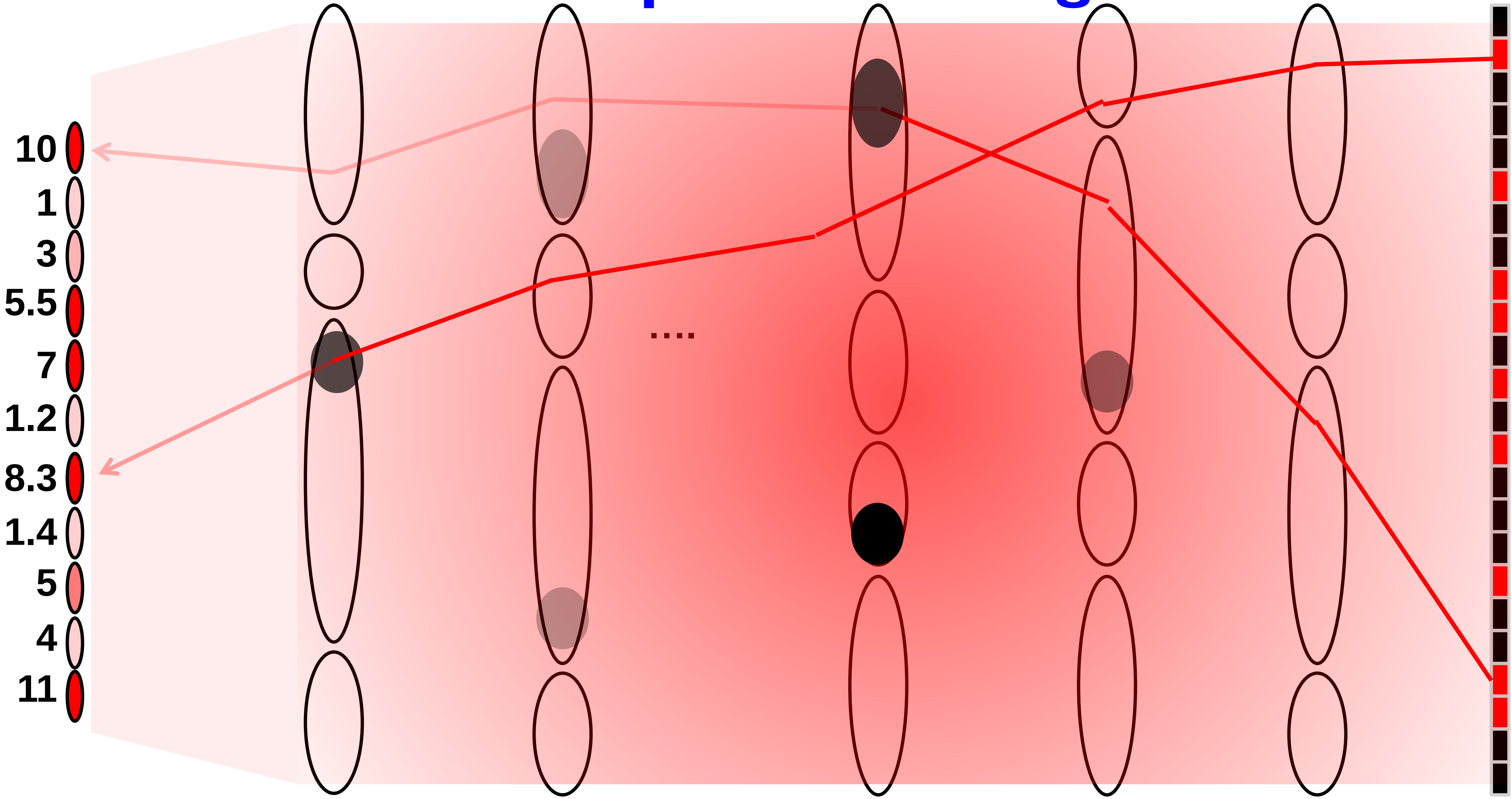


4차 벡터

$$\begin{bmatrix} 2 \\ 0.1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.1 \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

2차 벡터 2x4 행렬

Matrix computation using lens



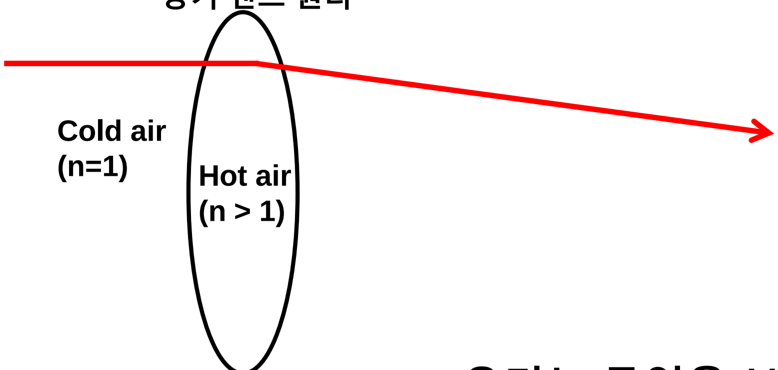
$$\begin{bmatrix} 10 \\ 1 \\ \cdots \\ \cdots \\ 23.2 \\ 1.3 \end{bmatrix} = \begin{bmatrix} \vdots & \cdots & \vdots \\ & \ddots & \\ & \cdots & \end{bmatrix} \times \begin{bmatrix} \vdots & \cdots & \vdots \\ & \ddots & \\ & \cdots & \end{bmatrix} \cdots \begin{bmatrix} \vdots & \cdots & \vdots \\ & \ddots & \\ & \cdots & \end{bmatrix} \times \begin{bmatrix} \vdots & \cdots & \vdots \\ & \ddots & \\ & \cdots & \end{bmatrix} \times \begin{bmatrix} \vdots & \cdots & \vdots \\ & \ddots & \\ & \cdots & \end{bmatrix} \times \begin{bmatrix} 2.3 \\ \cdots \\ \cdots \\ \cdots \\ 3.4 \\ 10 \end{bmatrix}$$

아지랑이

부엉이 벡터

https://www.youtube.com/watch?v=JhGCGNUf3EU

공기 렌즈 원리



영화 Matrix 중

https://giphy.com/explore/matrix-code

tenor.com

- 우리는 무엇을 보고 있는 것일까?
- 행렬의 곱셈을 실시간으로 보고 있는 것일까?
- 이 세상은 정말 Matrix (행렬) 일까??

HUFFPOST

뉴스 2016년 06월 07일 06시 41분 KST | 업데이트됨 2016년 06월 07일 06시 44분 KST

일론 머스크는 우리가 누군가의 '비디오 게임'이라고 생각한다

Andy Campbell
The Huffington Post

일론 머스크는 빨간 알약을 먹은 게 분명하다.

Patrick Fallon / Reuters

우리가 시뮬레이션 속에 있다는 가장 강한 논거는 아마 이것일 겁니다. 40년 전 우리에겐 퐁이 있었어요. 사각형 두 개와 점이 있는 게임이죠. 게임이란 이런 거였어요.
40년이 지난 지금, 우리에겐 수백만 명이 동시에 플레이하는 포토리얼리스틱 3D 시뮬레이션 게임이 있어요. 매년 더 나아지죠. 곧 우리에겐 가상 현실, 증강 현실이 생길 겁니다.
개선 속도를 어떻게 예측한다 해도, 이런 게임들은 현실과 구분이 불가능해질 겁니다. 발전 속도가 지금의 천 분의 일로 떨어진다 해도요. 진화에서는 아무것도 아닌 시간인 1만 년 뒤의 미래는 어떻지 상상해 봅시다.
우리는 현실과 구분이 불가능한 게임이 존재하는 미래로 가는 노선에 오른 게 분명하고, 이런 게임은 셋탑 박스든 PC든, 어떤 장비에서든 할 수 있을 거예요. 그리고 그런 컴퓨터나 셋탑 박스가 수십억 개 있겠죠. 그러면 우리가 있는 곳이 기저 현실일 가능성이 수십억 분의 일이 되는 겁니다.

엘론 머스크 "미래 인류, 가상 아닌 현실에 살 확률 10억분의 1"

2016.06.03 13:58

2

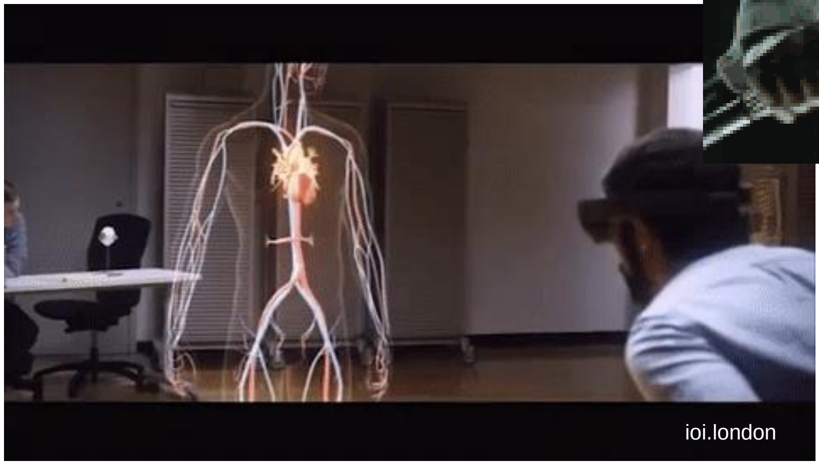
찜

기술 진보로 가상·증강현실 세계 펼쳐져
미래엔 게임과 현실 구분 불가능
기술 진보, '인류 멸망'시에만 멈출 것

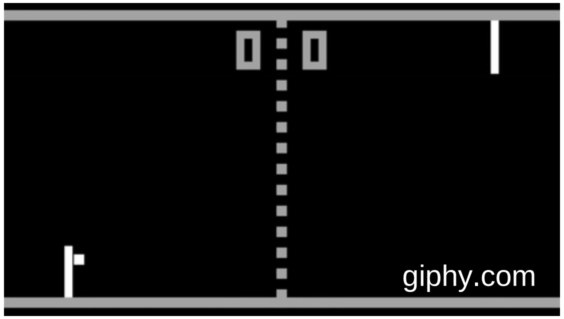
Evolution of cyber world

2060s
?

2020s
VR



1980s
Pong game



- **How old are you in 2060s?**

How old are you in 2060?

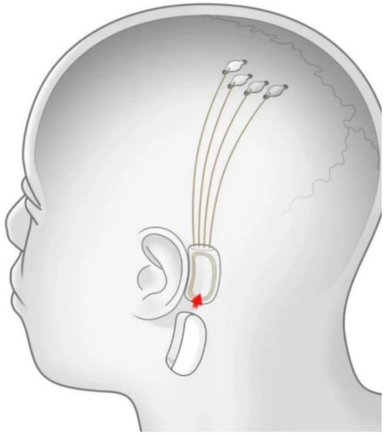
- I'm 72, you?
- 다들 이러고 있을까요???

Neuralink

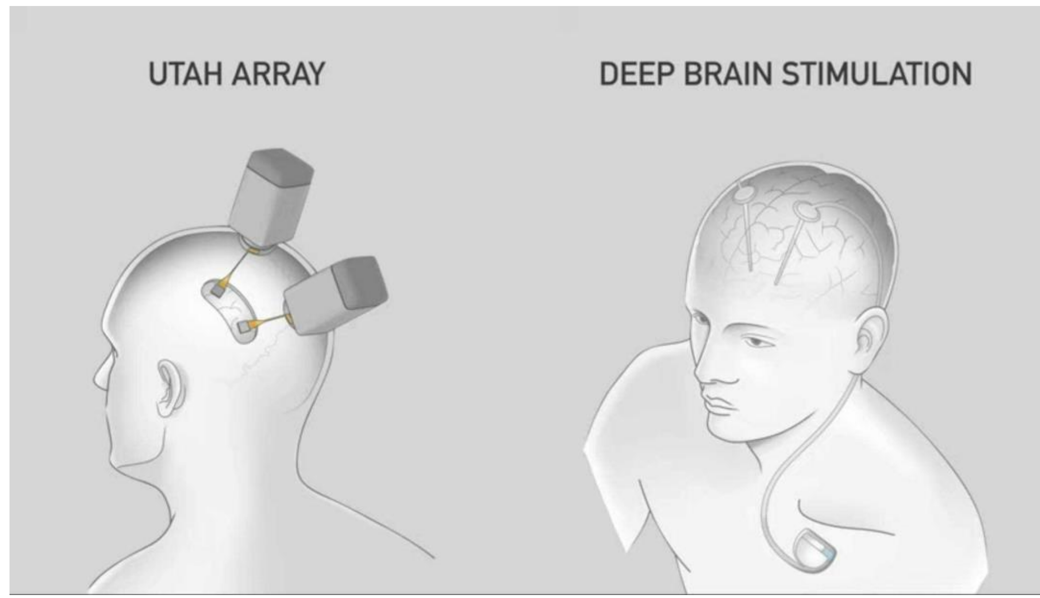
Elon Musk Says People Will Eventually Consume Music Through Brain Chip

Startup company Neuralink was founded to help us keep up with artificial intelligence

The past and future of streaming music, according to Elon Musk



consequence.net

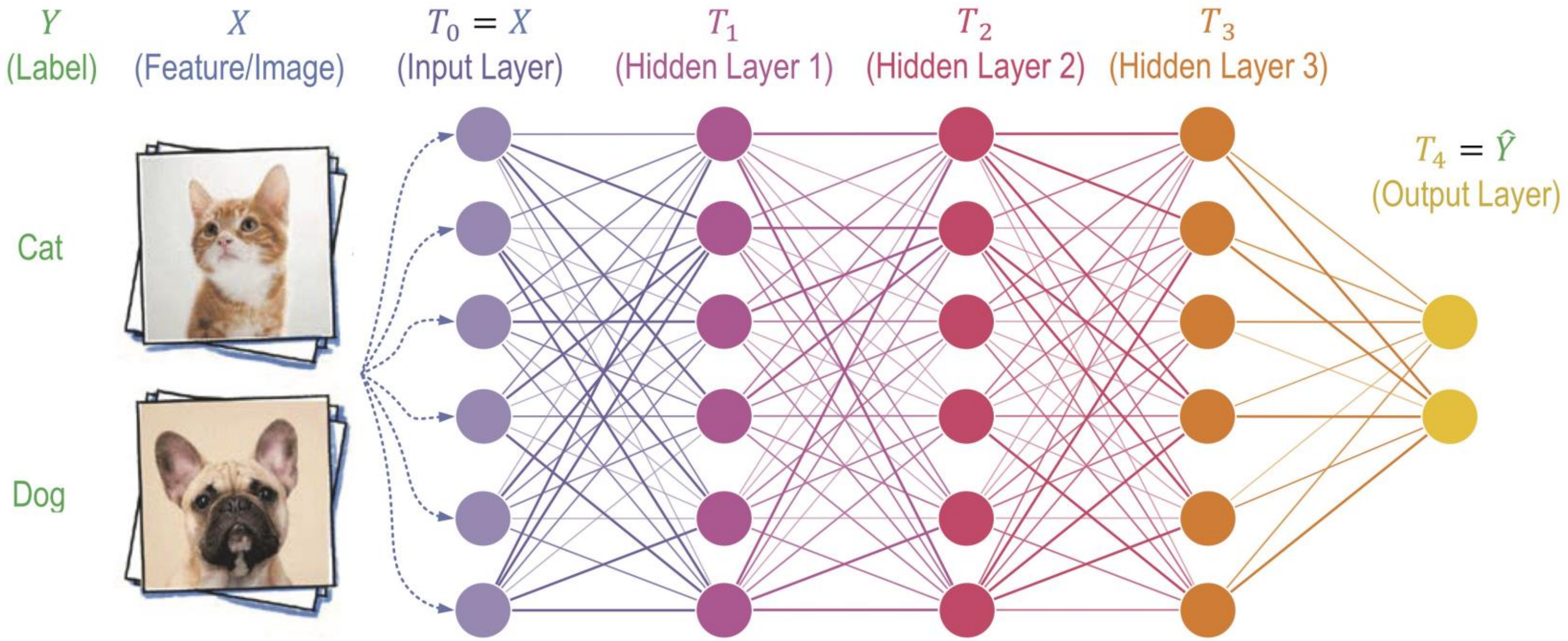


insideevs.com

- **Elon Musk's startup company**

Neural network
&
matrix multiplication

Deep neural network

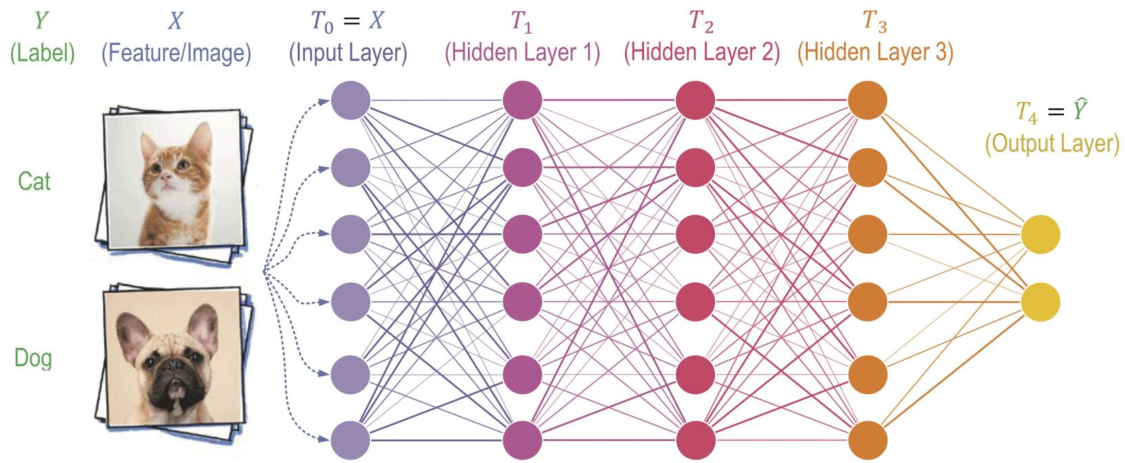


medium.com

- 다들 neural net 이 뭔지는 아시죠? (적어도 조금은?)

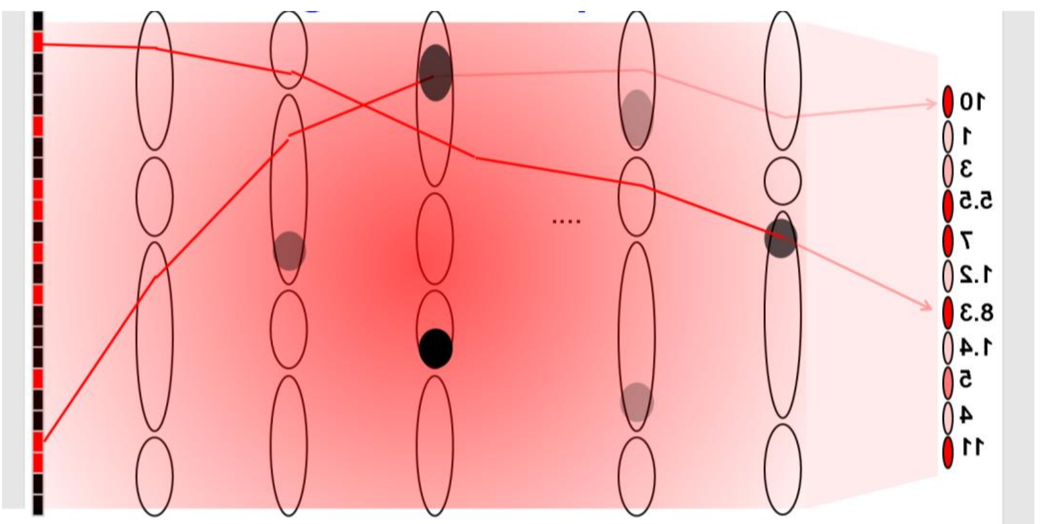
비슷하게 생겼나요?

Neural net

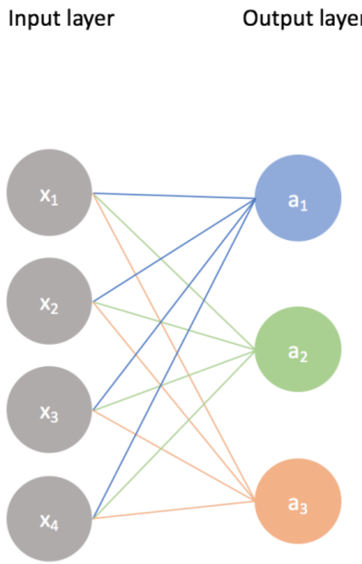


medium.com

Lens net

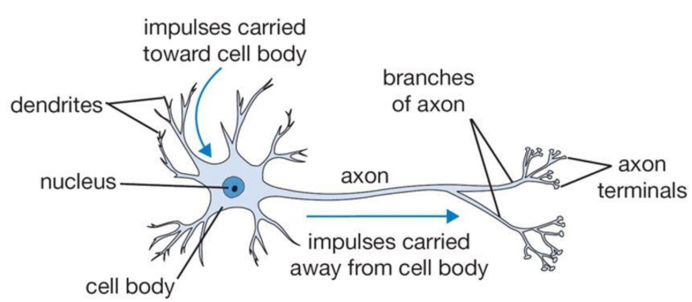


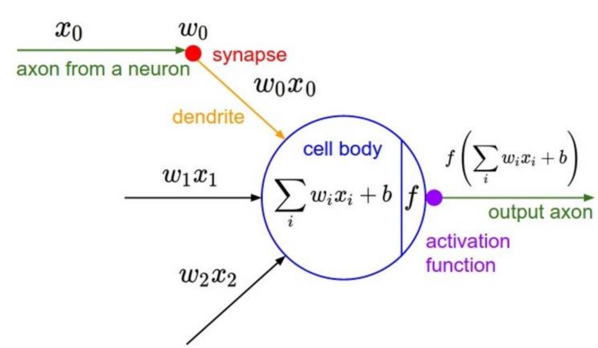
Neural net and matrix-vector multiplications



Using multiple observations

$$\begin{bmatrix} w_1 & w_2 & w_3 & w_4 \\ w_1 & w_2 & w_3 & w_4 \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix} \begin{array}{c} \begin{array}{cccc} \textit{Observation 1} & \textit{Observation 2} & \textit{Observation 3} & \textit{Observation 4} \end{array} \\ \begin{bmatrix} x_1 & x_1 & x_1 & x_1 \\ x_2 & x_2 & x_2 & x_2 \\ x_3 & x_3 & x_3 & x_3 \\ x_4 & x_4 & x_4 & x_4 \end{bmatrix} \end{array} + \begin{bmatrix} b \\ b \\ b \end{bmatrix} \xrightarrow{\textit{activation}} \begin{array}{c} \begin{array}{cccc} \textit{Observation 1} & \textit{Observation 2} & \textit{Observation 3} & \textit{Observation 4} \end{array} \\ \begin{bmatrix} a_1 & a_1 & a_1 & a_1 \\ a_2 & a_2 & a_2 & a_2 \\ a_3 & a_3 & a_3 & a_3 \end{bmatrix} \end{array}$$



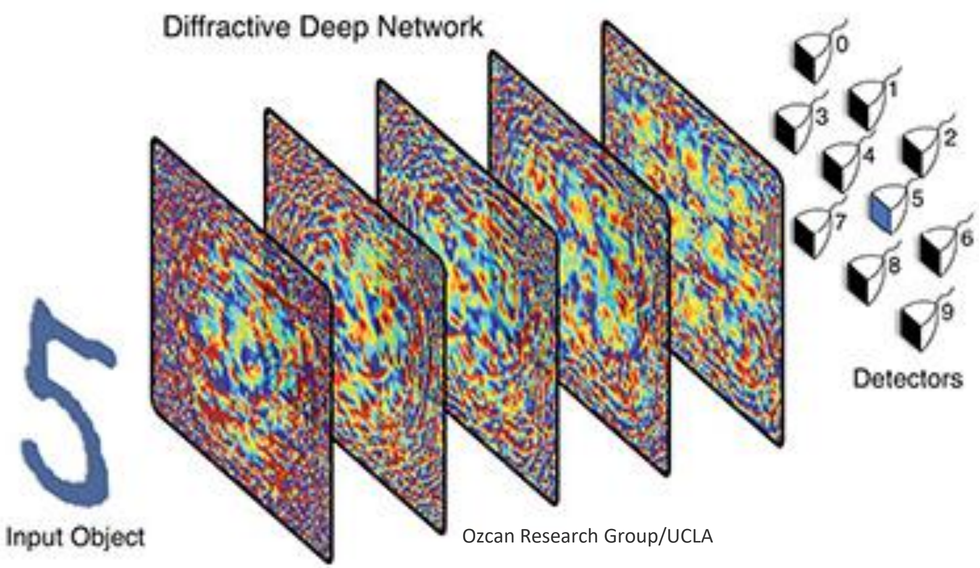


https://www.jeremyjordan.me/intro-to-neural-networks/

- **Each layer of neural net is matrix multiplication**
- **Just like the lens net**

Optical deep neural networks (UCLA, Ozcan's group)

Optical neural net



Ozcan Research Group/UCLA

RESEARCH

OPTICAL COMPUTING

All-optical machine learning using diffractive deep neural networks

Xing Lin[1,2,3]*, Yair Rivenson[1,2,3]*, Nezih T. Yardimci[1,3], Muhammed Veli[1,2,3], Yi Luo[1,2,3], Mona Jarrahi[1,3], Aydogan Ozcan[1,2,3,4]†

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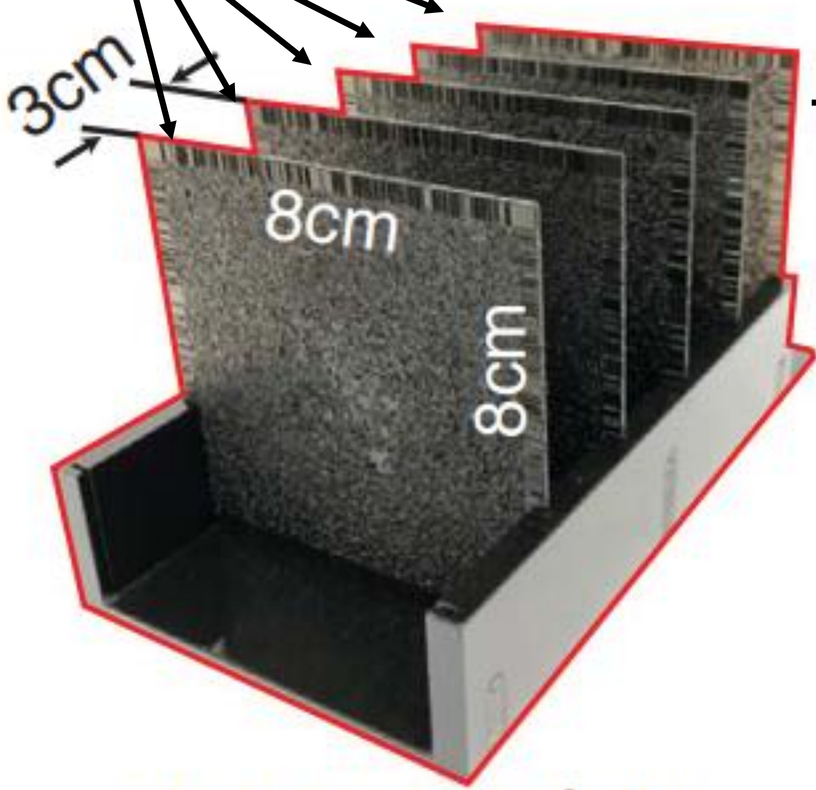
Science 2018

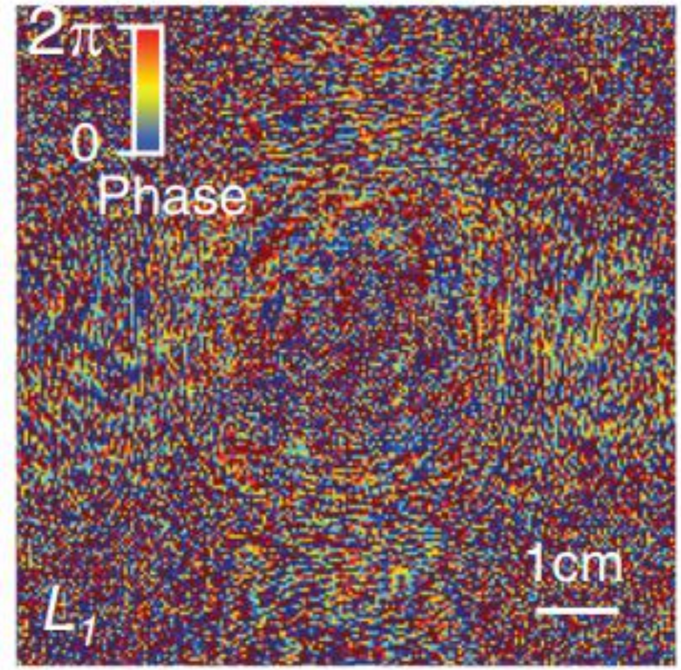
그것을 실제로 만들었습니다! (UCLA)

3차원 프린터로
만든 렌즈 복합체

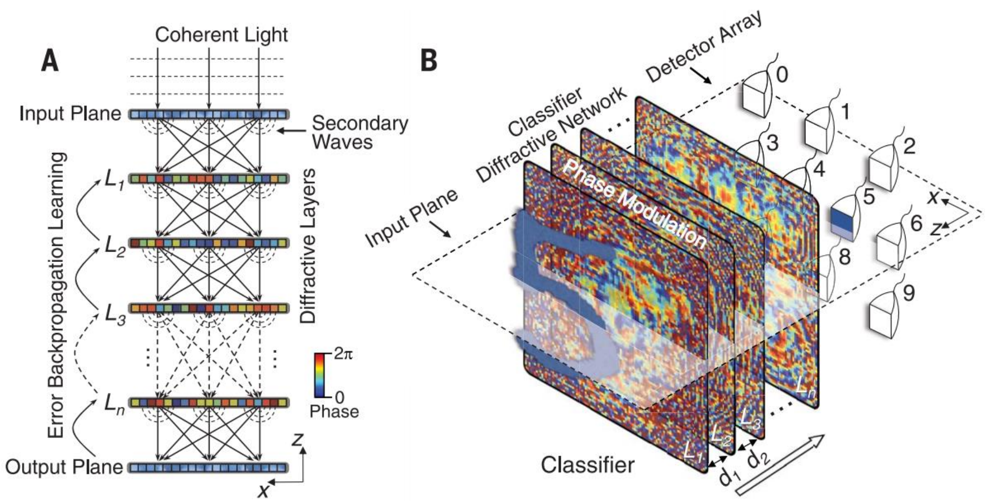


3D Printed D^{2}NN
(Classifier)

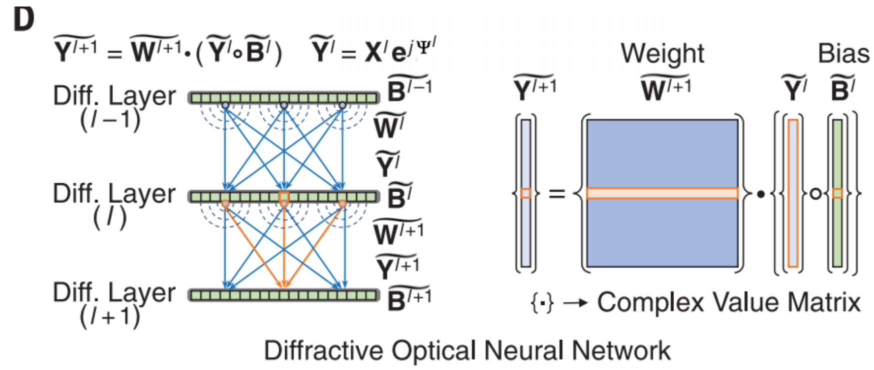
렌즈 복합체 디자인



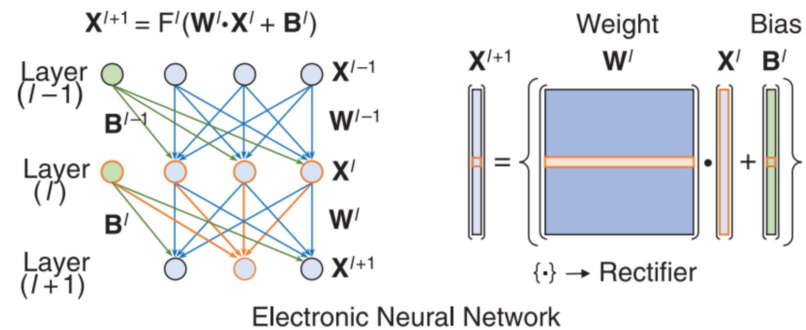
렌즈 복합체 한 층 ≈ neural net 한 층



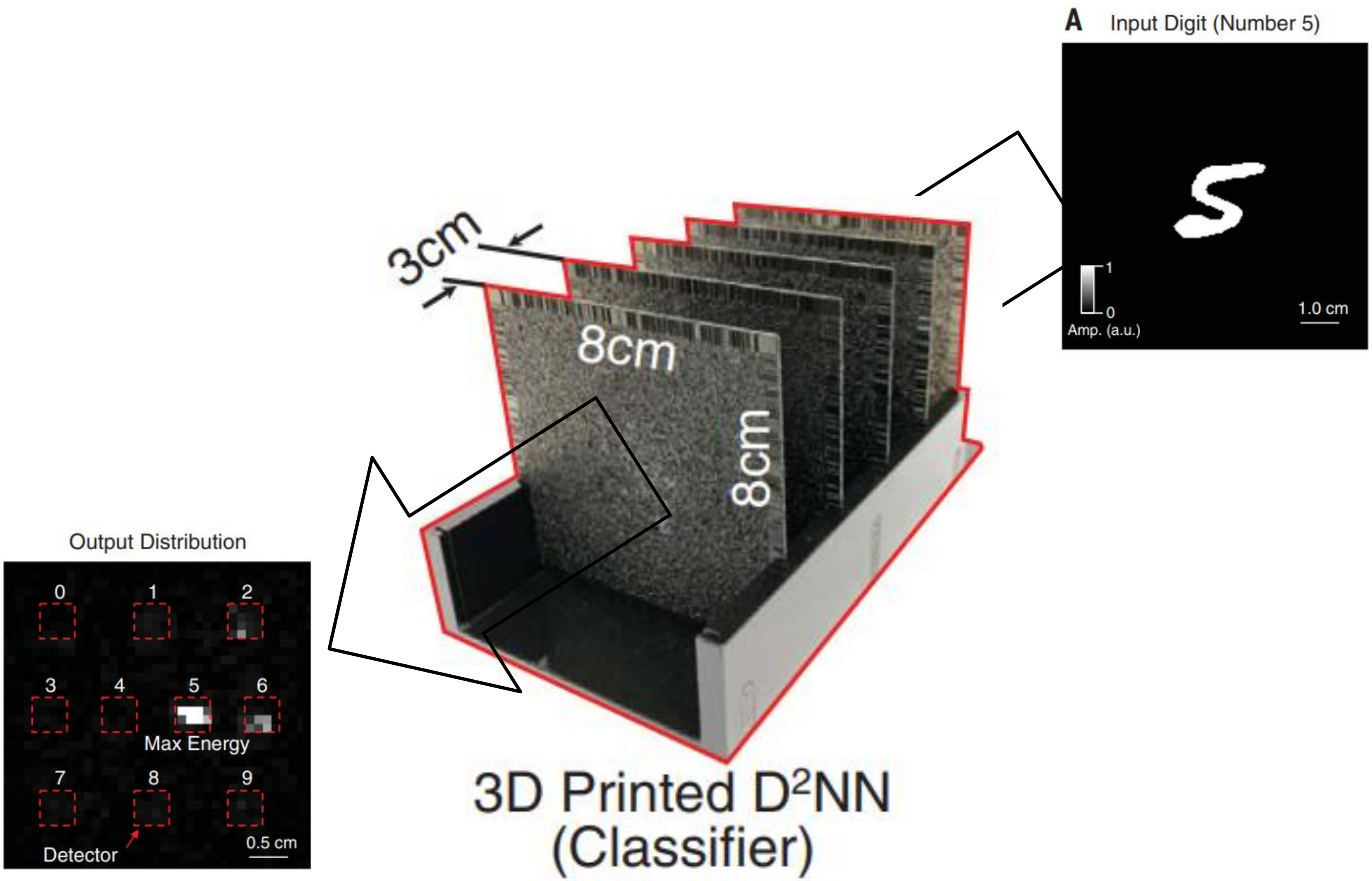
Optical neural net



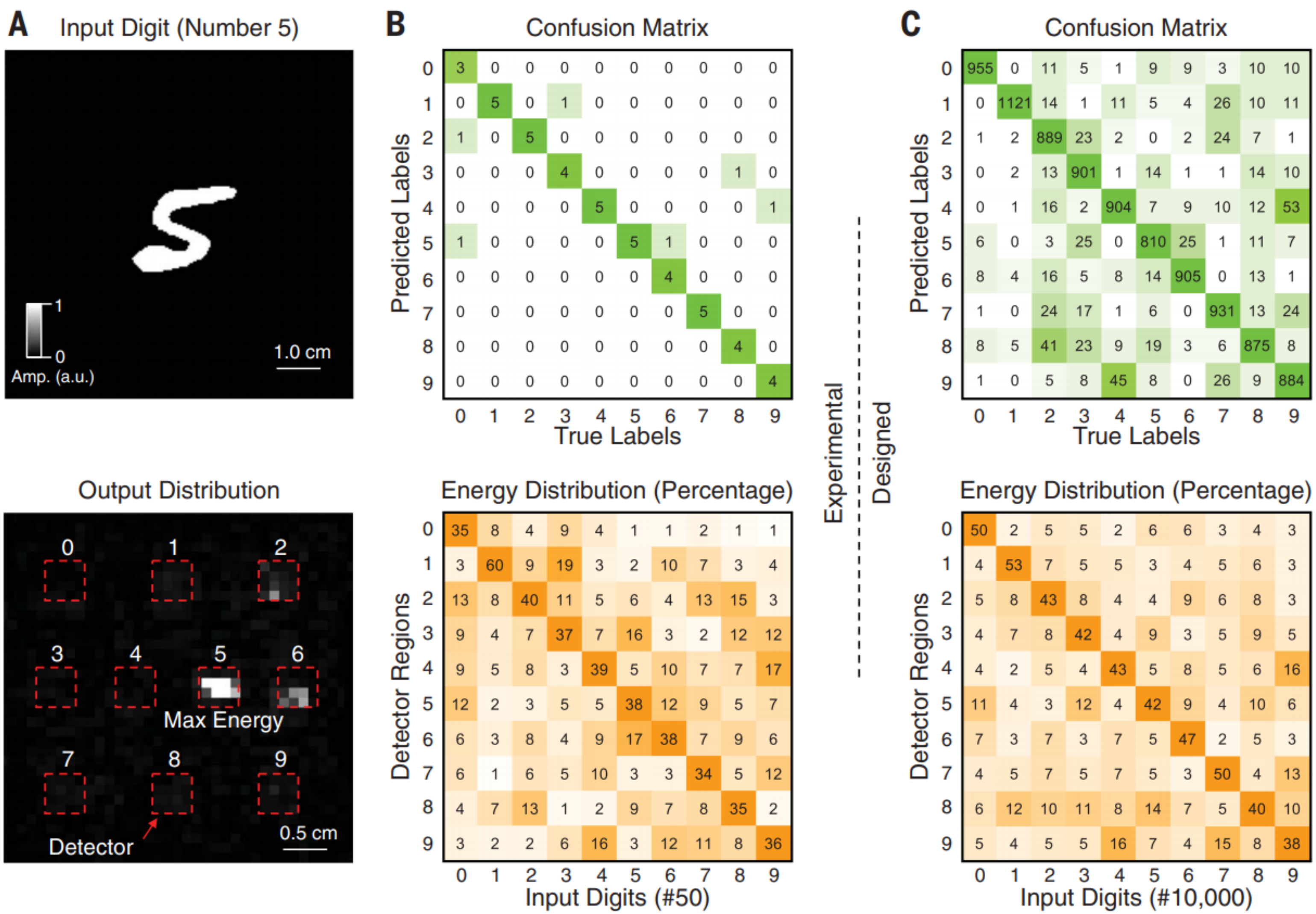
Electronic neural net



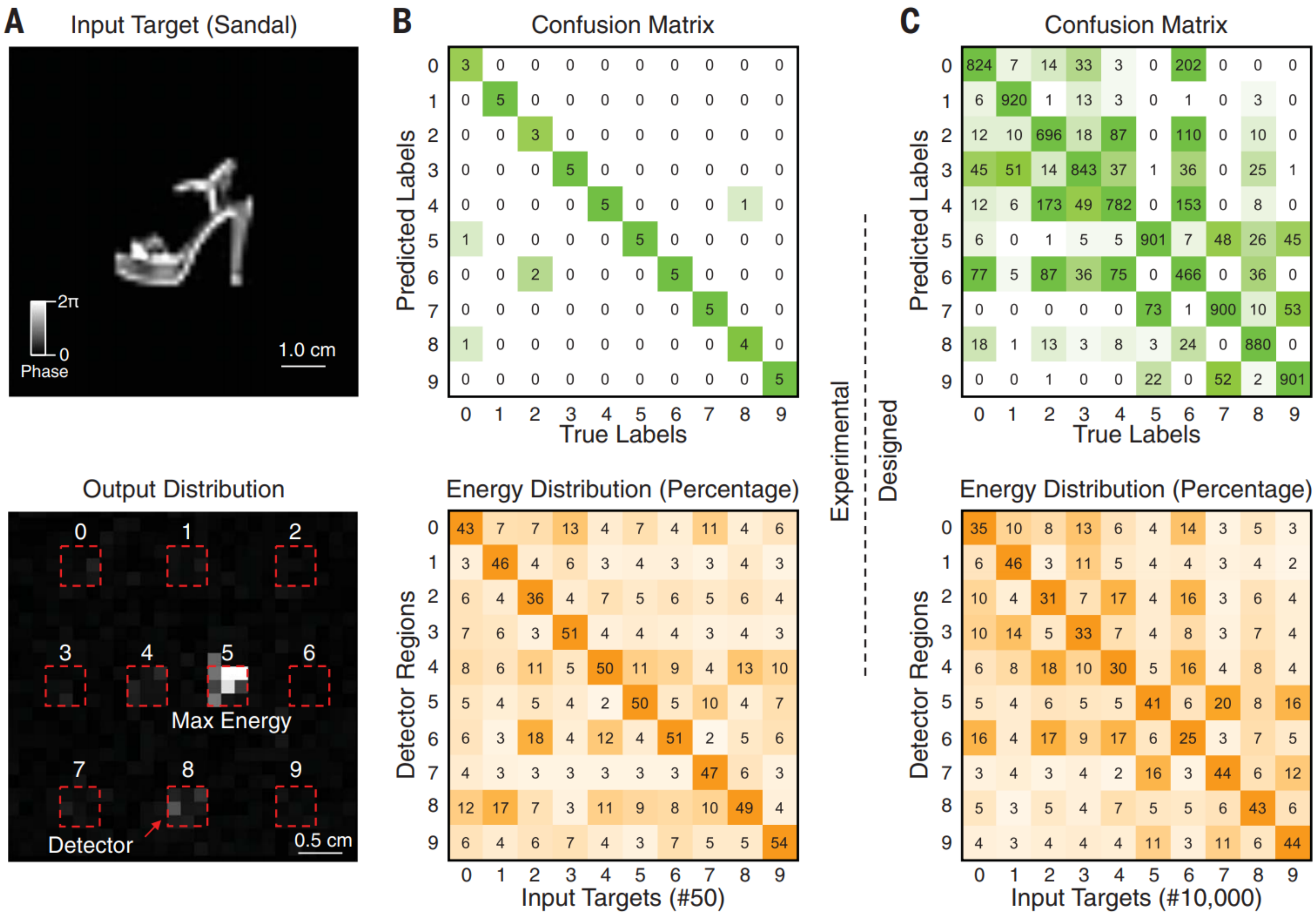
렌즈를 통해 보는 것 만으로 답을 알 수 있다?!



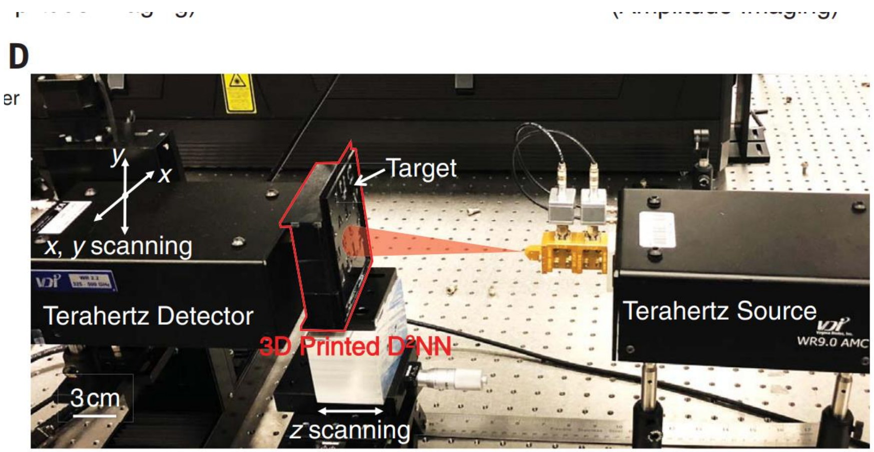
숫자 분류

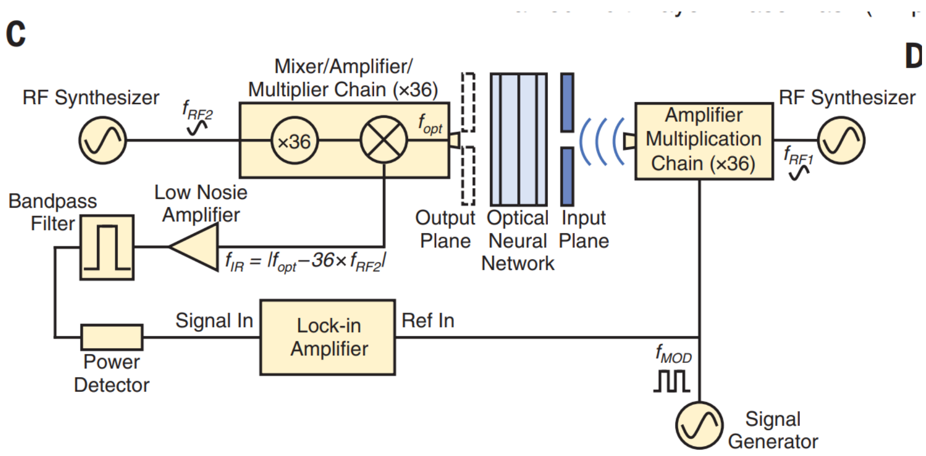

A
Input Digit (Number 5)
Amp. (a.u.)
1.0 cm
Output Distribution
Max Energy
Detector
0.5 cm
B
Confusion Matrix
Predicted Labels
True Labels
Energy Distribution (Percentage)
Detector Regions
Input Digits (#50)
Experimental
Designed
C
Confusion Matrix
Predicted Labels
True Labels
Energy Distribution (Percentage)
Detector Regions
Input Digits (#10,000)

물체 분류


A
Input Target (Sandal)
2π
0
Phase
1.0 cm
Output Distribution
0 1 2
3 4 5 6
Max Energy
7 8 9
Detector
0.5 cm
B
Confusion Matrix
Predicted Labels
3 0 0 0 0 0 0 0 0 0
0 5 0 0 0 0 0 0 0 0
0 0 3 0 0 0 0 0 0 0
0 0 0 5 0 0 0 0 0 0
0 0 0 0 5 0 0 0 1 0
1 0 0 0 0 5 0 0 0 0
0 0 2 0 0 0 5 0 0 0
0 0 0 0 0 0 0 5 0 0
1 0 0 0 0 0 0 0 4 0
0 0 0 0 0 0 0 0 0 5
True Labels
Energy Distribution (Percentage)
Detector Regions
43 7 7 13 4 7 4 11 4 6
3 46 4 6 3 4 3 3 4 3
6 4 36 4 7 5 6 5 6 4
7 6 3 51 4 4 4 3 4 3
8 6 11 5 50 11 9 4 13 10
5 4 5 4 2 50 5 10 4 7
6 3 18 4 12 4 51 2 5 6
4 3 3 3 3 3 3 47 6 3
12 17 7 3 11 9 8 10 49 4
6 4 6 7 4 3 7 5 5 54
Input Targets (#50)
Experimental
Designed
C
Confusion Matrix
Predicted Labels
824 7 14 33 3 0 202 0 0 0
6 920 1 13 3 0 1 0 3 0
12 10 696 18 87 0 110 0 10 0
45 51 14 843 37 1 36 0 25 1
12 6 173 49 782 0 153 0 8 0
6 0 1 5 5 901 7 48 26 45
77 5 87 36 75 0 466 0 36 0
0 0 0 0 0 73 1 900 10 53
18 1 13 3 8 3 24 0 880 0
0 0 1 0 0 22 0 52 2 901
True Labels
Energy Distribution (Percentage)
Detector Regions
35 10 8 13 6 4 14 3 5 3
6 46 3 11 5 4 4 3 4 2
10 4 31 7 17 4 16 3 6 4
10 14 5 33 7 4 8 3 7 4
6 8 18 10 30 5 16 4 8 4
5 4 6 5 5 41 6 20 8 16
16 4 17 9 17 6 25 3 7 5
3 4 3 4 2 16 3 44 6 12
5 3 5 4 7 5 5 6 43 6
4 3 4 4 4 11 3 11 6 44
Input Targets (#10,000)

전체 시스템





- **~1mm 파장의 빛을 이용 (눈에는 안보임)**
  - **cf. 가시광 파장 (~500 nm)**
- **빛을 만들어내고 읽는 데에 특수한 장치 필요**
  - **Quiz: 왜 가시광을 안 썼을까요??**
- **그런데, 문제가 바뀌면 (e.g. 숫자 분류 → 물체 분류) 렌즈를 다시 프린트 해야 하네….**
- **푸는건 빛의 속도, 하지만 문제 로딩 하는데 시간이 너무 많이 걸리자나….**

nature photonics

ARTICLES

https://doi.org/10.1038/s41566-021-00796-w

Check for updates

Large-scale neuromorphic optoelectronic computing with a reconfigurable diffractive processing unit

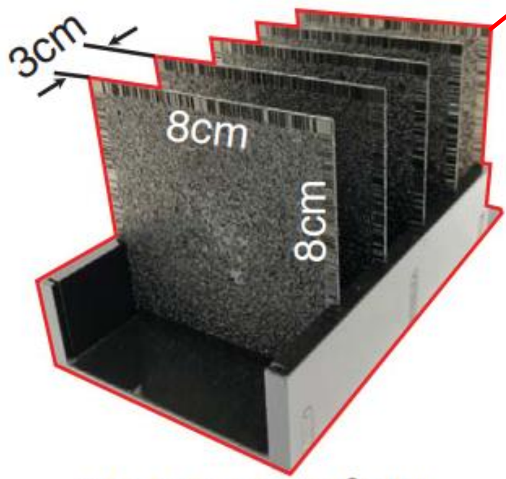
Tiankuang Zhou[1,2,3,4], Xing Lin[1,2,5] ✉, Jiamin Wu[1,2], Yitong Chen[1,2], Hao Xie[1,2], Yipeng Li[1,2], Jingtao Fan[1,2], Huaqiang Wu[5,6,7], Lu Fang[2,3,6] ✉ and Qionghai Dai[1,2,6] ✉

There is an ever-growing demand for artificial intelligence. Optical processors, which compute with photons instead of electrons, can fundamentally accelerate the development of artificial intelligence by offering substantially improved computing performance. There has been long-term interest in optically constructing the most widely used artificial-intelligence architecture, that is, artificial neural networks, to achieve brain-inspired information processing at the speed of light. However, owing to restrictions in design flexibility and the accumulation of system errors, existing processor architectures are not reconfigurable and have limited model complexity and experimental performance. Here, we propose the reconfigurable diffractive processing unit, an optoelectronic fused computing architecture based on the diffraction of light, which can support different neural networks and achieve a high model complexity with millions of neurons. Along with the developed adaptive training approach to circumvent system errors, we achieved excellent experimental accuracies for high-speed image and video recognition over benchmark datasets and a computing performance superior to that of cutting-edge electronic computing platforms.

- **Beijing university & Tsinghua university**
- **이번 달 (2021년 5월) Nature photonics 표지 논문**

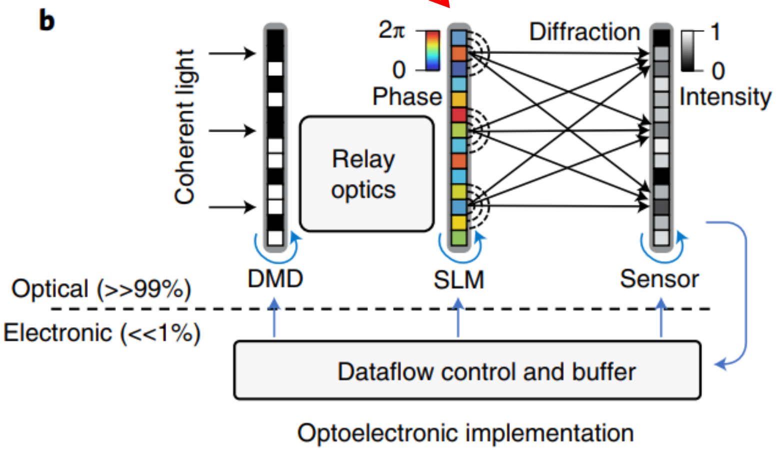
Replacing lens with spatial light modulator

UCLA



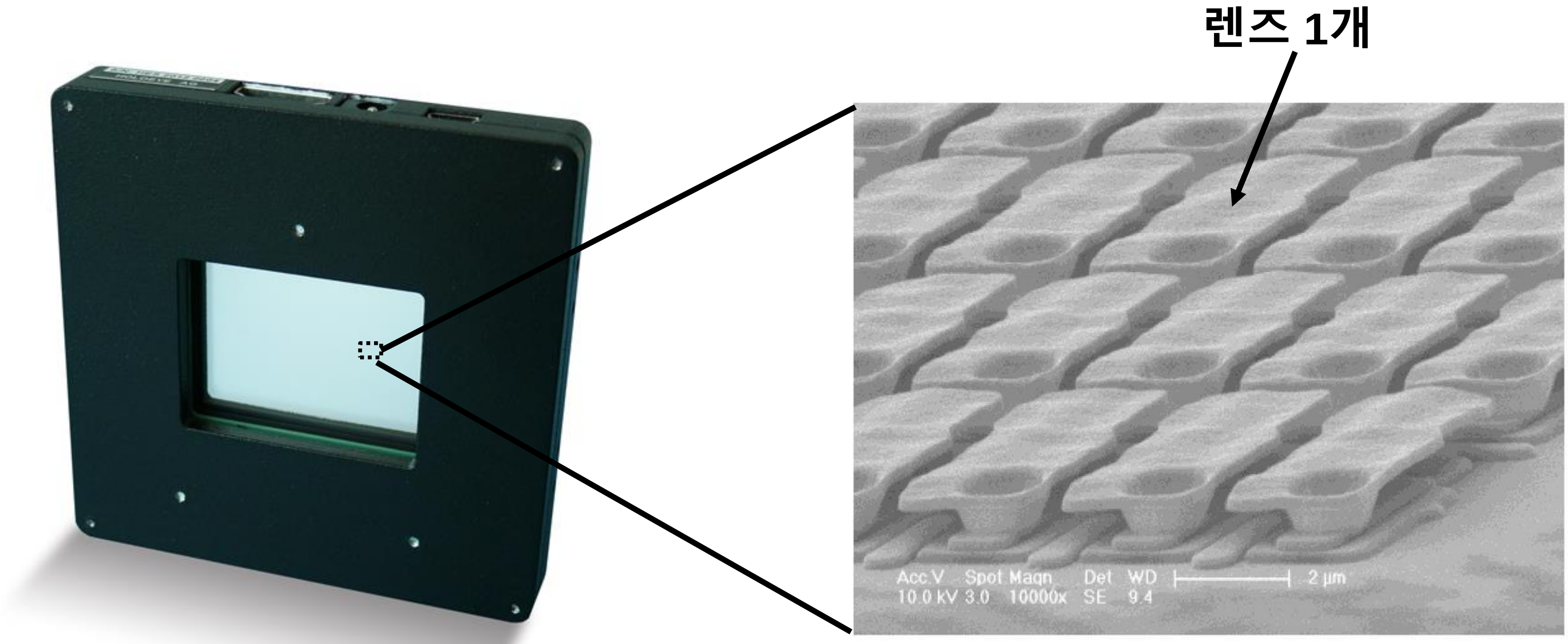
3D Printed D²NN
(Classifier)

Beijing & Tsinghua



- **Spatial light modulator (SLM)을 이용하여 렌즈를 대체**
  - **가시광 (700nm) 이용**
- **Refresh rate: 14 kHz (1초에 1만4천번 문제 바꿀수 있다)**
- **계산은 여전히 빛의 속도로**

Spatial light modulator

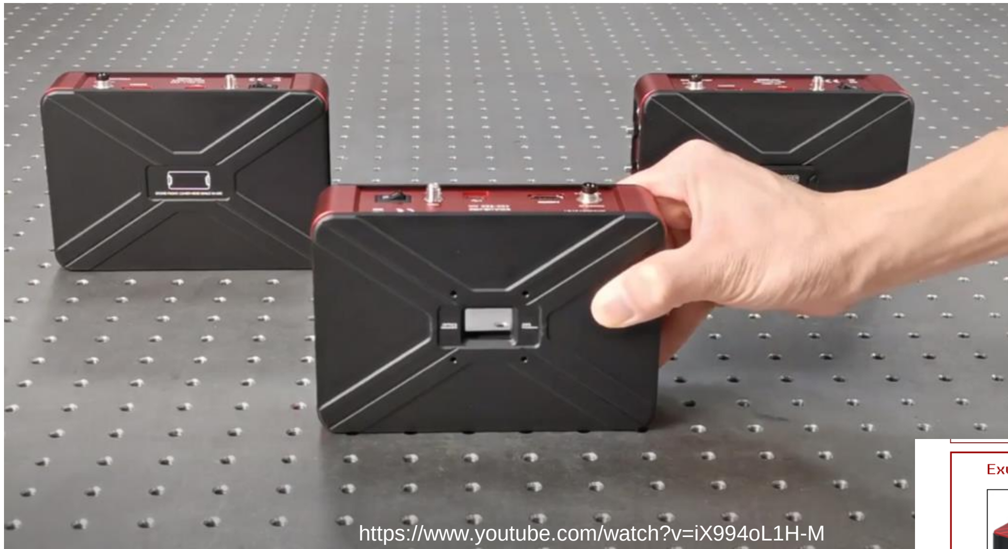


holoeye.com/

J.-H. Yang, et al., SPIE (2019)
ETRI, Korea

- 굴절율 조절 가능한 초소형 렌즈 (~2000x1000 개) 어레이

Spatial light modulator



Exulus Spatial Light Modulator with Full HD Resolution

Zoom

- Liquid Crystal on Silicon (LCoS) with Aluminum Coating for 400 - 850 nm
- 1920 x 1080 (Full HD) Resolution
- HDMI and USB 2.0 Input
- Optic Axis: 45°
- Housing Dimensions: 172.0 mm x 110.0 mm x 81.6 mm

The EXULUS-HD1(/M) Spatial Light Modulator has a 1920 x 1080 (Full HD) LCoS panel with an aluminum reflective coating for operation over the 400 - 850 nm wavelength range. It also features four operation modes including extended phase shift range and a high frame rate mode (up to 180 Hz). The bottom and two sides of the housing each offer two 8-32 (M4) tapped holes for post mounting. The front panel includes four 4-40 taps for 30 mm cage system compatibility; we do not recommend connecting this spatial light modulator to a cage system for applications that require precise alignment.

Click to Enlarge

The back panel of the EXULUS-HD1(/M) provides USB and HDMI ports for connecting the SLM to a PC, power supply input, and an on/off switch.

Key Specifications[a]									
Item #	Operating Wavelength	Panel Resolution	Fill Factor	Panel Active Area	Pixel Pitch	Phase / Retardance Range[b]	Frame Rate	Fluctuation/ Flickering (RMS)	Output Trigger
EXULUS-HD1(/M)	400 - 850 nm	1920 x 1080 (Full HD)	>93%	12.5 mm x 7.1 mm	6.4 µm	2π at 633 nm (Std.) 4.7π at 532 nm (Ext.)	60 Hz (Standard) or 180 Hz (Frame Boost[c])	<1% (Standard) <5% (Extended)	N/A

a. Complete specifications may be found on the *Specs* tab.
b. Angles of incidence other than 0° will result in phase shifts that differ from the programmed pattern. Angles of up to 10° are possible without significantly affecting performance.
c. Frame Boost Mode (referred to as Triple Mode in the software) plays the R, G, and B channels of the HDMI signal in succession, for an overall frame rate of 180 Hz.

Based on your currency / country selection, your order will ship from Newton, New Jersey

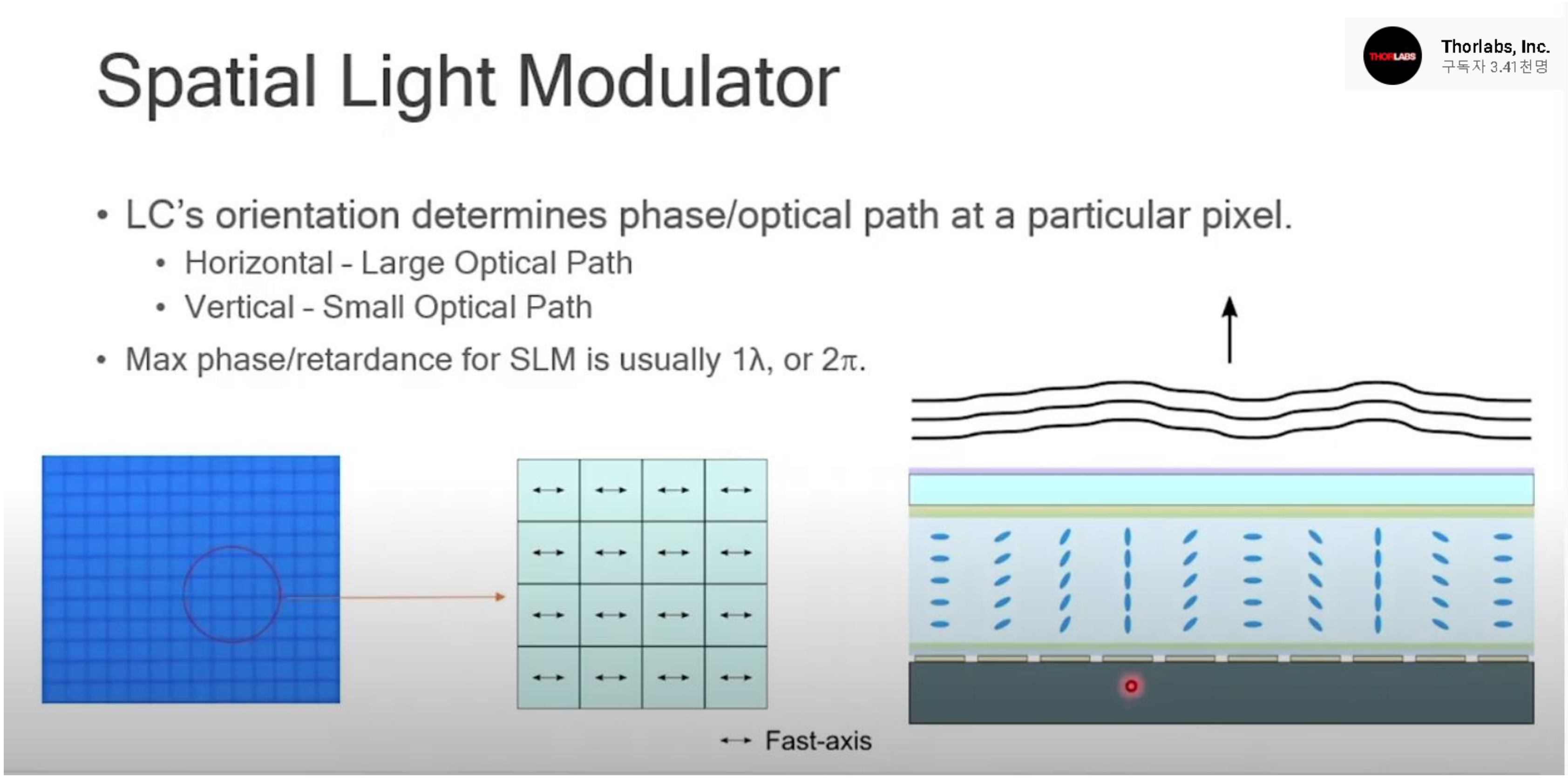
+1	Qty	Docs	Part Number - Imperial		Price	Available
			EXULUS-HD1	Spatial Light Modulator, 1920 x 1080, 400 - 850 nm, 8-32 Taps	$18,260.75	Today

+1	Qty	Docs	Part Number - Metric		Price	Available
			EXULUS-HD1/M	Spatial Light Modulator, 1920 x 1080, 400 - 850 nm, M4 Taps	$18,260.75	Today

Add To Cart

- **You can buy one on internet (~$10,000)**

Spatial light modulator

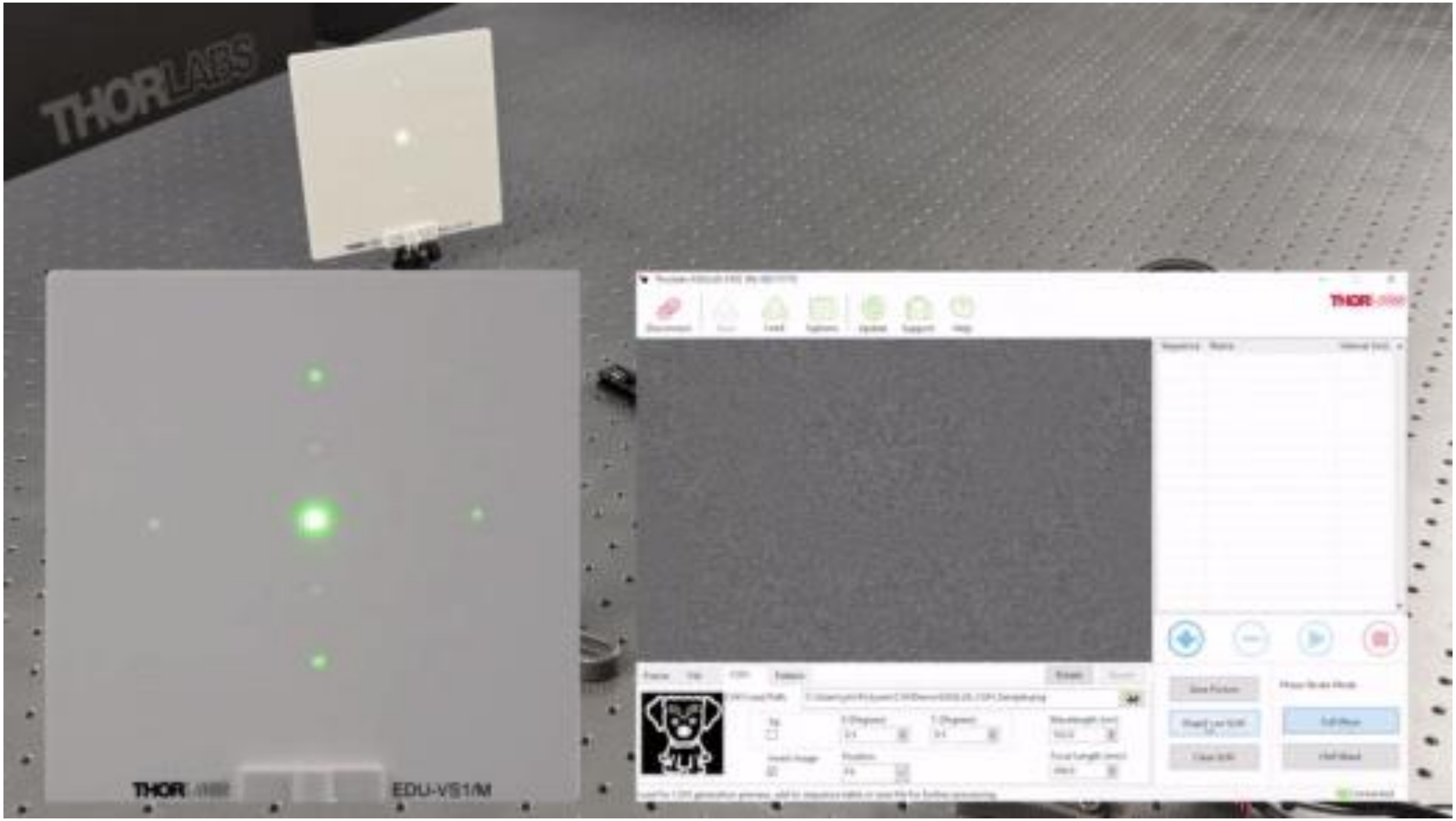


https://www.youtube.com/watch?v=iX994oL1H-M

• 액정: 전기를 걸어주면 굴절율이 변화 한다

→ 전기를 적절히 걸어주면 렌즈를 만들 수 있다

SLM demo



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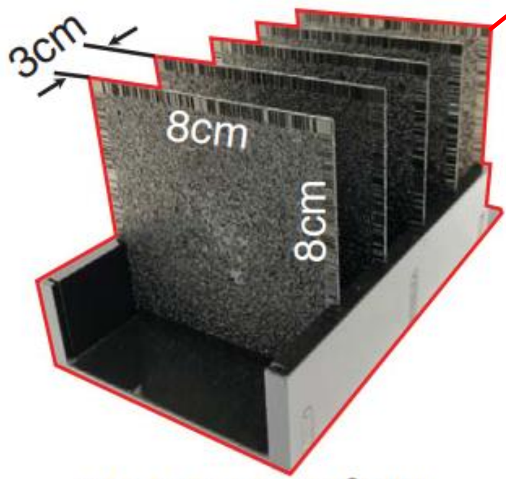
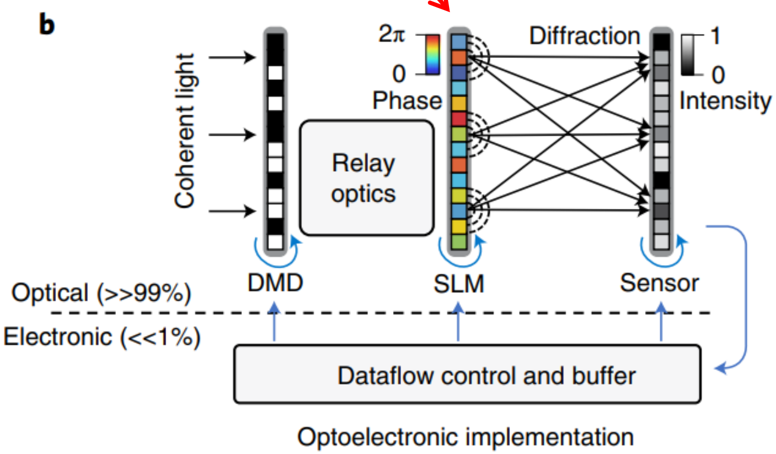


3D Printed D^{2}NN
(Classifier)

Beijing & Tsinghua



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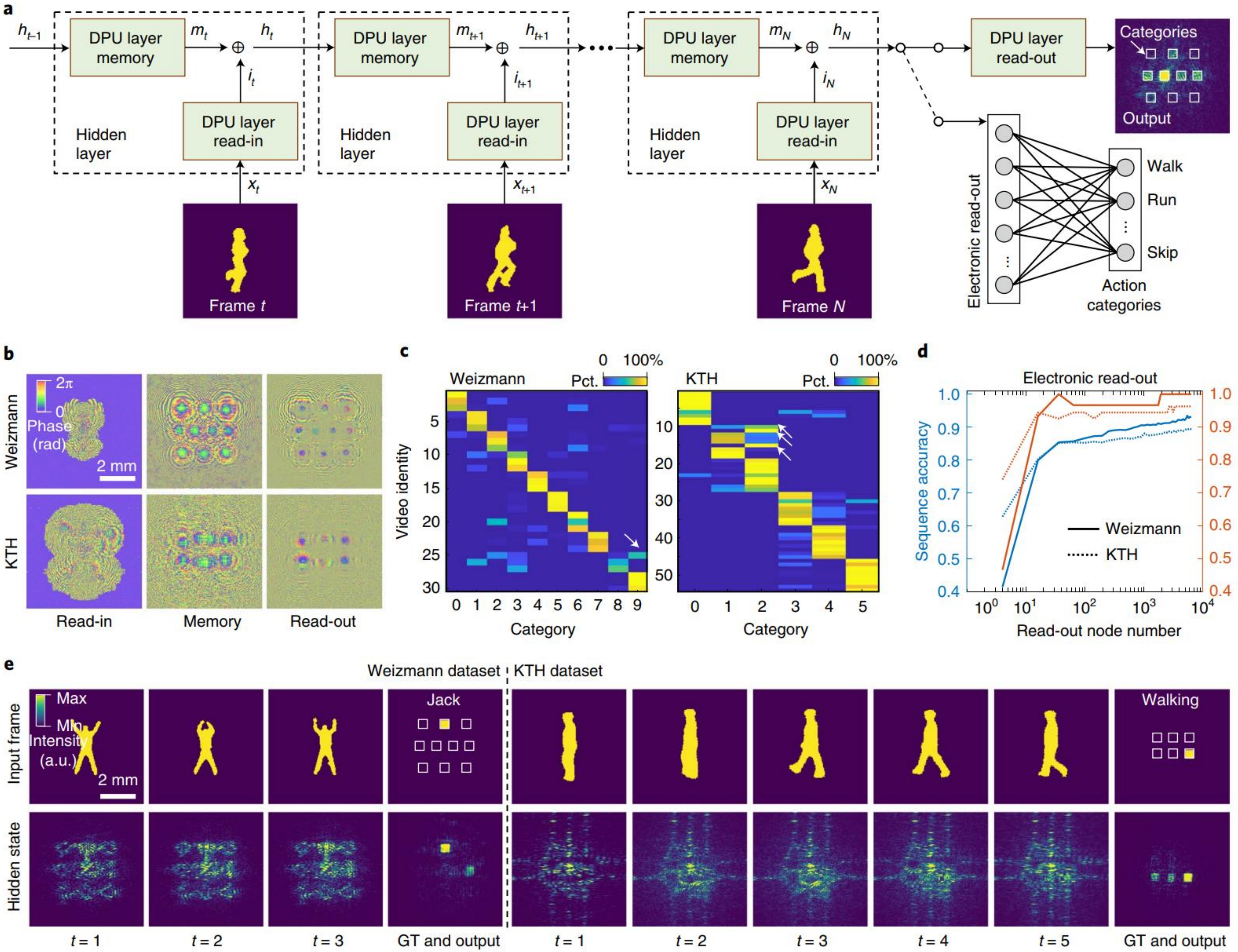
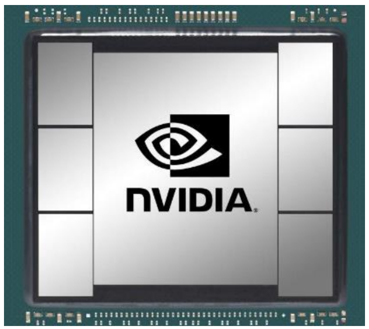


a
DPU layer memory
DPU layer read-in
Hidden layer
Frame t
Frame t+1
Frame N
DPU layer read-out
Categories
Output
Electronic read-out
Walk
Run
Skip
Action categories
b
Weizmann
KTH
Phase (rad)
2 mm
Read-in
Memory
Read-out
c
Weizmann
KTH
Pct.
0
100%
Video identity
Category
d
Electronic read-out
Sequence accuracy
Action accuracy
Weizmann
KTH
Read-out node number
e
Weizmann dataset
KTH dataset
Input frame
Hidden state
Max
Min
Intensity (a.u.)
2 mm
Jack
Walking
t = 1
t = 2
t = 3
t = 4
t = 5
GT and output

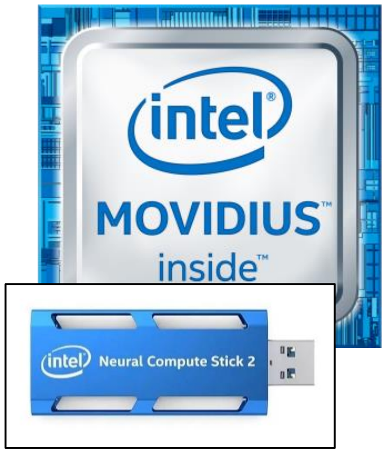
Waveguide version of Optical neural network

Hardware accelerators: what's next?

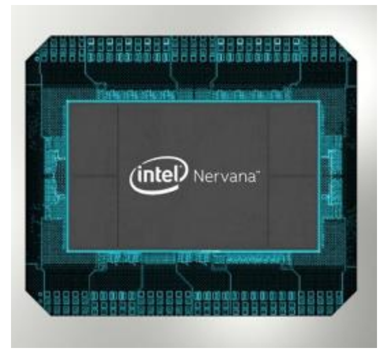
GPU
(Graphics Processing Unit)



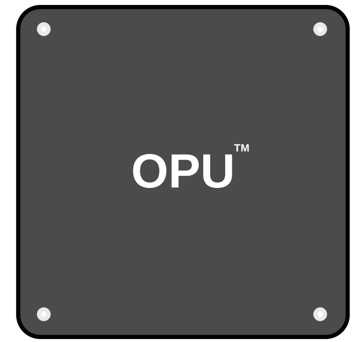
VPU
(Vision Processing Unit)



NNP
(Neural Network Processor)



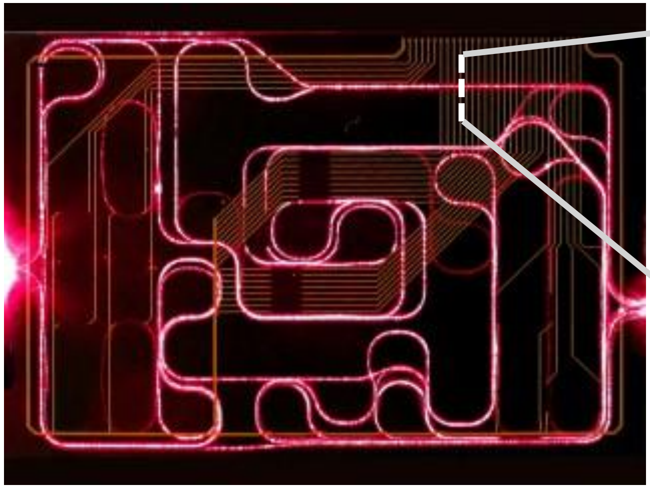
OPU?
(Optical Processing Unit)



- **하드웨어 가속기: 특정 연산에 특화된 칩**
- **최근 일반적인 연산을 위한 CPU 대신 특수한 연산을 위해 만들어진 하드웨어 가속기들에 대한 연구 및 양산이 이루어 지고 있음**

Optical Waveguides on PIC

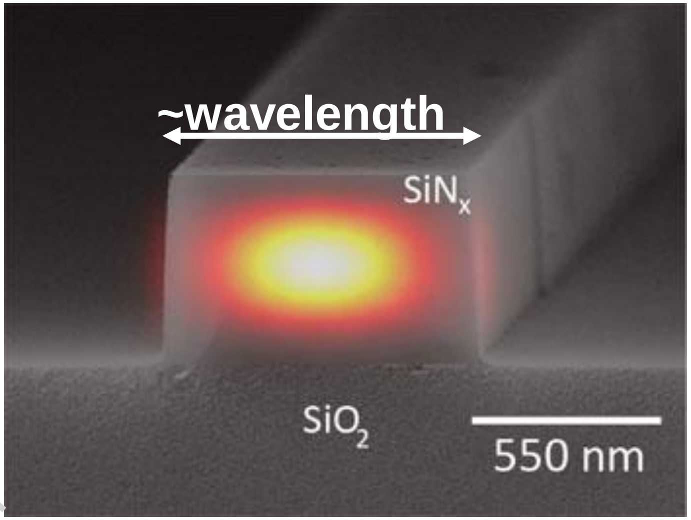
PIC



www.phiconference.com

~cm

Waveguide cross-section

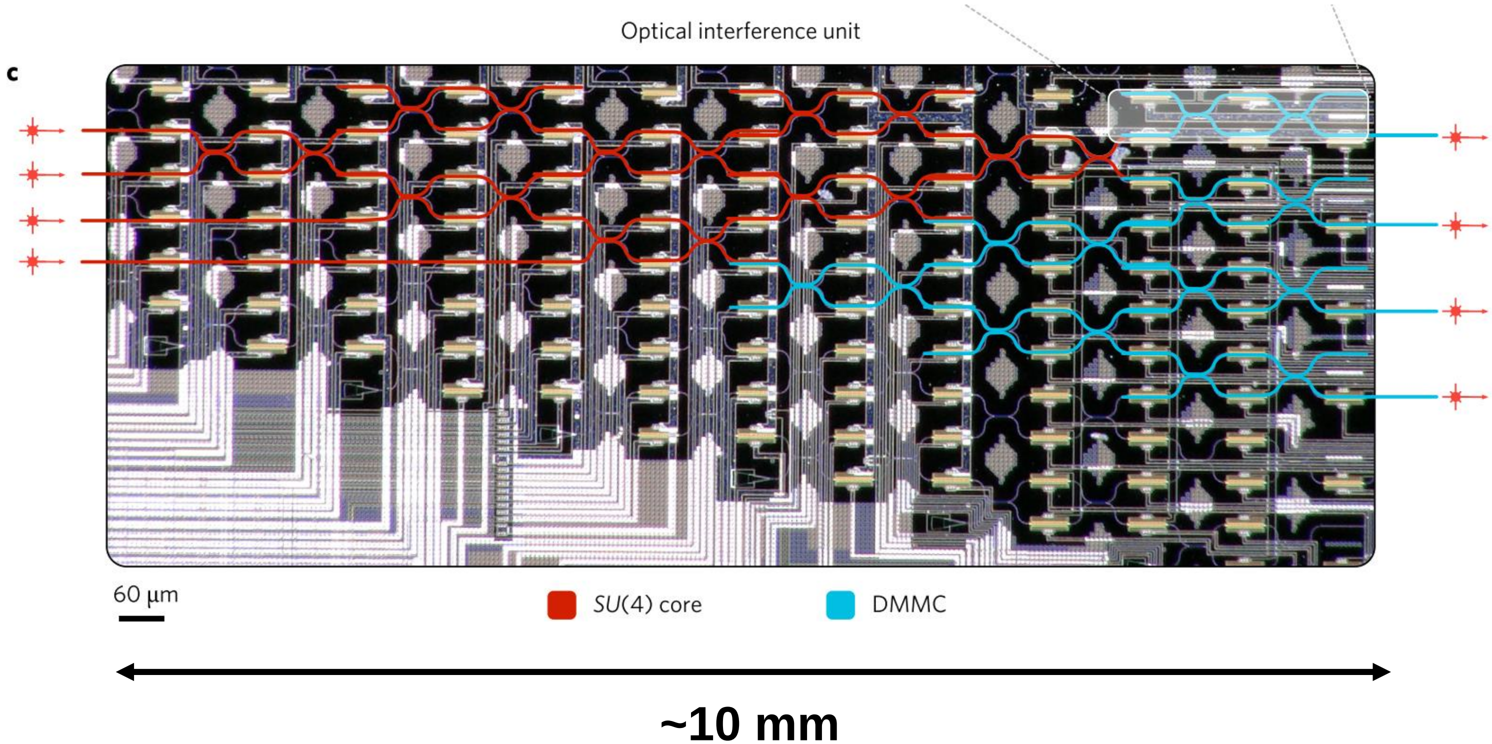


nist.gov

- **Light is guided by total internal reflection (TIR)**
- **Can be miniaturized down to ~wavelength (400 nm ~ 2 um)**

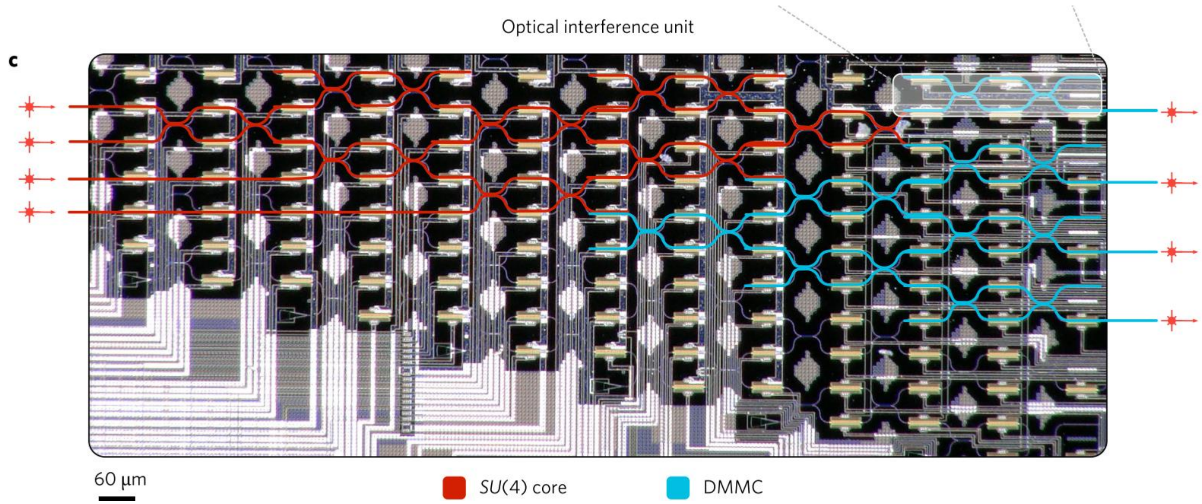
Optical neural net on a chip

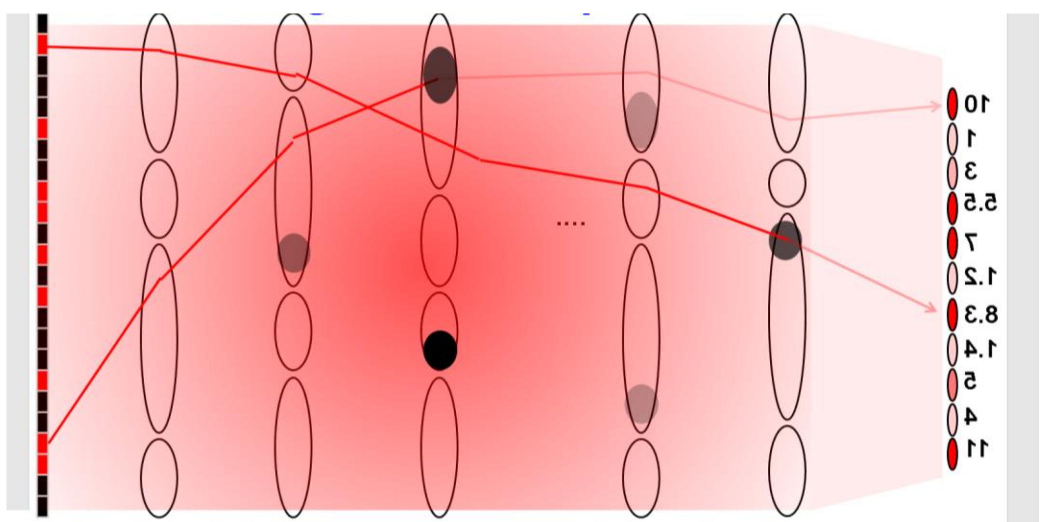
MIT (Dirk Englund), Nat Phot, 2017



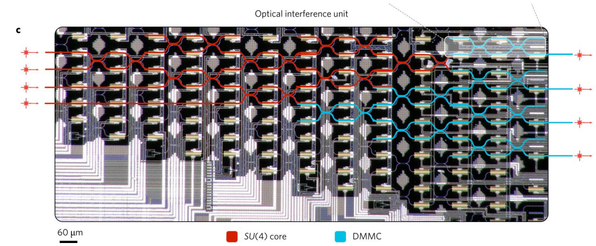
- **Building optical neural network using waveguides**
  - **i.e. Photonic Integrated Circuits (PIC)**

Look similar?



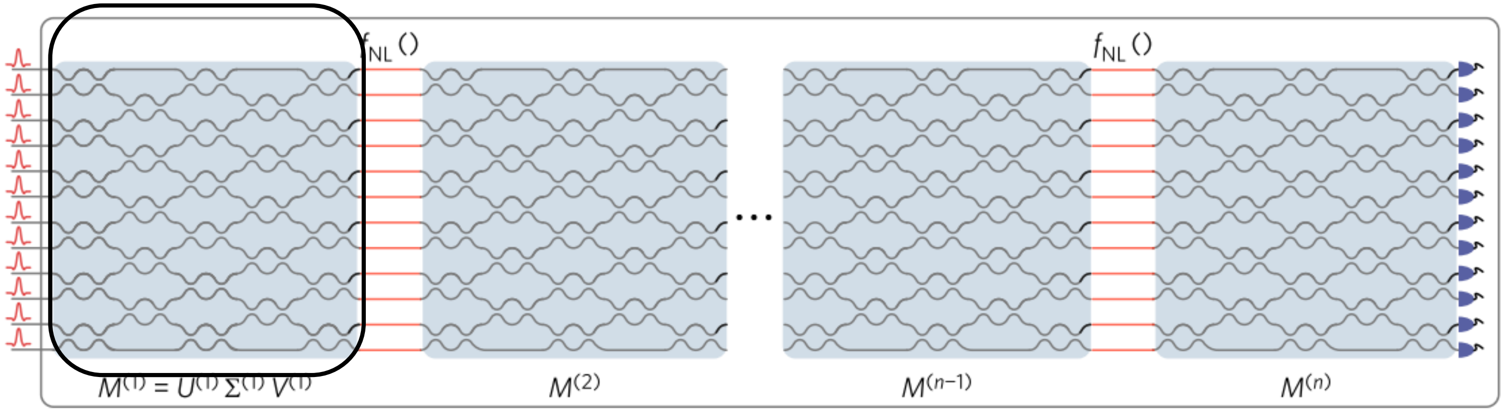


Optical neural net on a chip



Waveguide 복합체
(phase shifter, splitter, etc.)

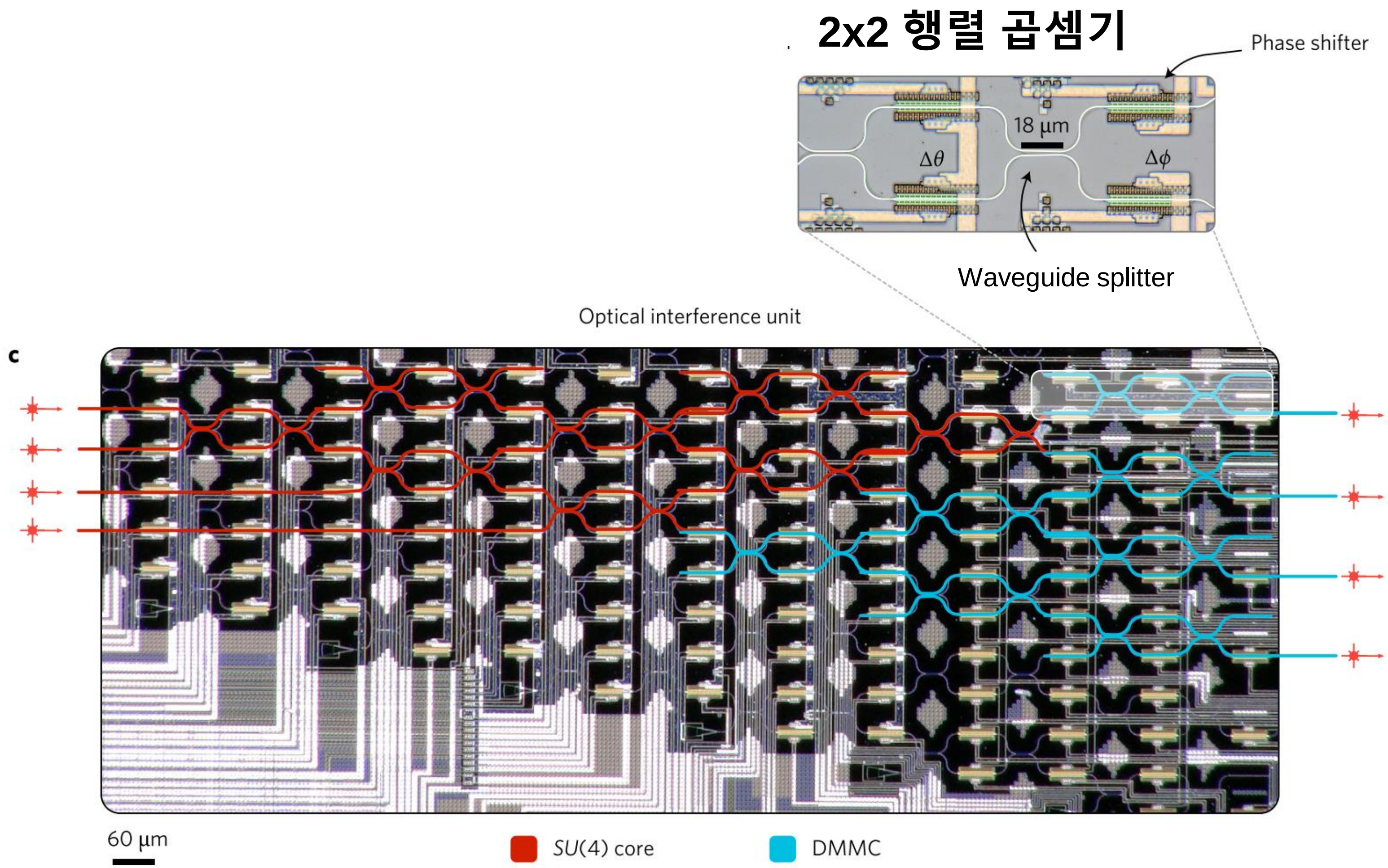
Waveguide map



Photonic integrated circuit

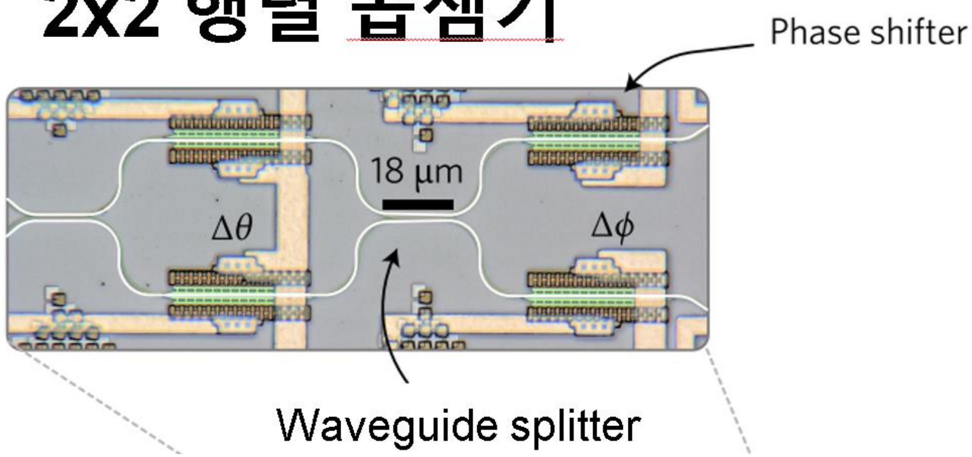
- **Waveguide, phase shifter, splitter를 적절히 조합하면 원하는 방향으로 빛을 보낼 수 있다.**
- **상상 되나요?**

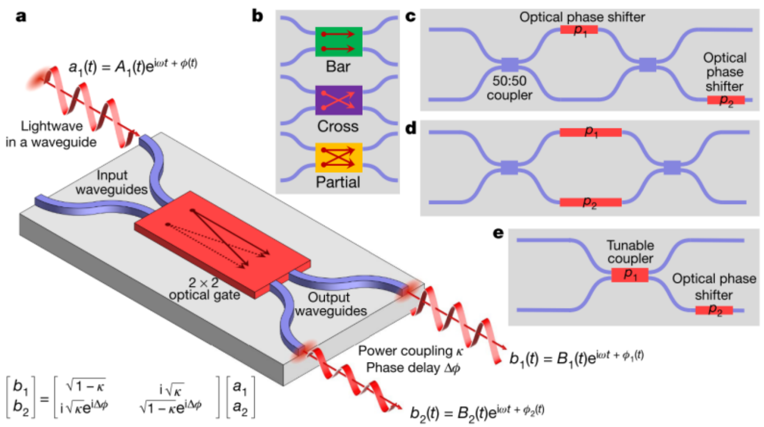
General matrix calculation using waveguide complex



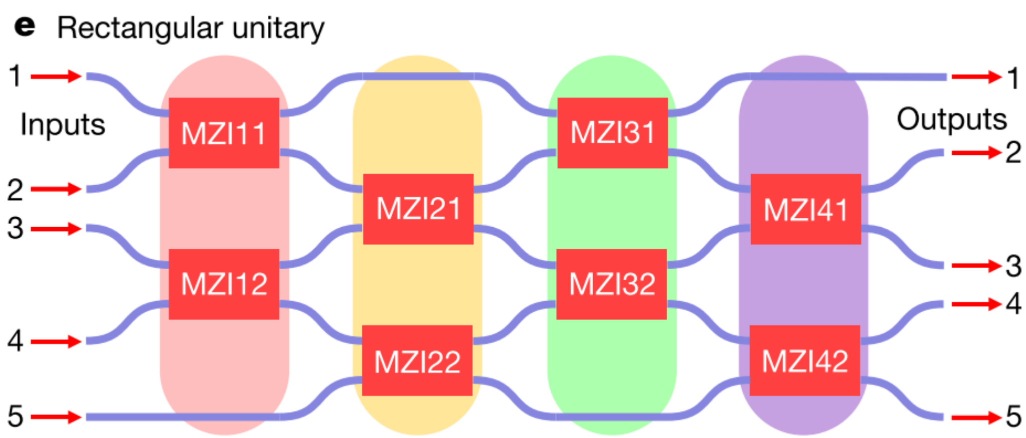
You can make any matrix using waveguide complex

2x2 행렬 곱셈기



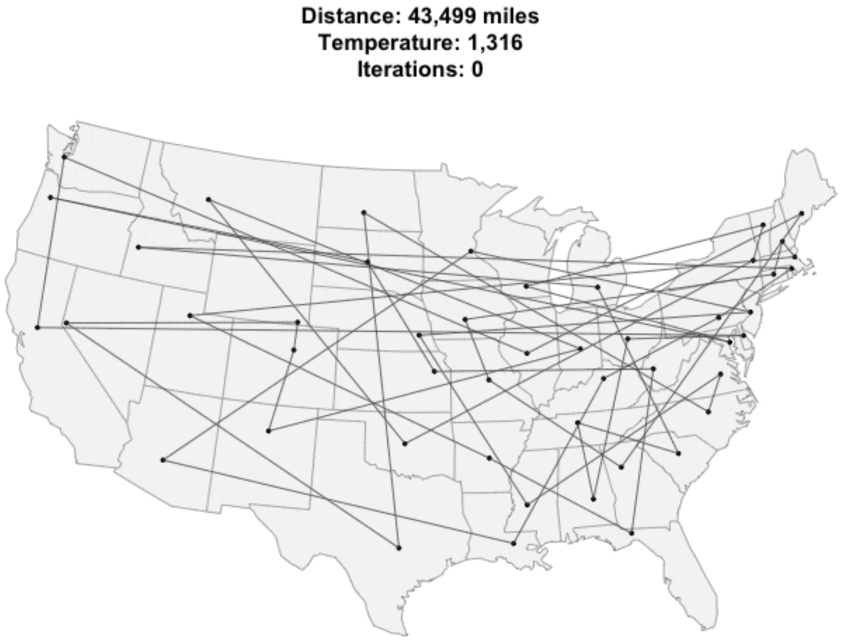


5x5 matrix multiplier



Optical Ising machine on a chip

50개의 도시를 최단거리로 도는 방법은?

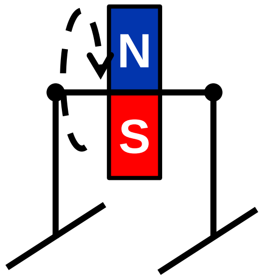


toddwschneider.com

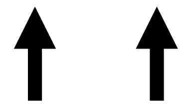
- $\frac{n!}{2}$ 가지의 조합: 50 개의 도시 → 1.5x10^{64} 가지의 조합
- 슈퍼컴퓨터로도 정확한 답을 못 찾는 문제
  - 경험적인 (heuristic) 방법으로 근사적인 답 만을 구할 수 있음
- Traveling salesman problem 이라는 computer science 분야의 유명한 문제
- 자율주행체의 경로 탐색 등에 응용

자석 방향 문제 (Ising problem)

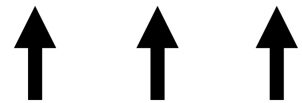
Free to rotate



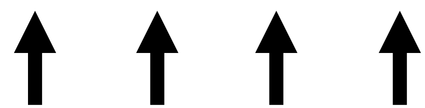
2 magnets



3 magnets



4 magnets

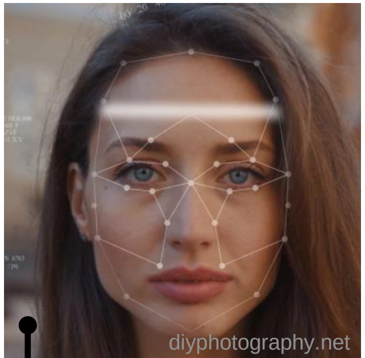


- It is a NP-hard problem
- N magnets → 2^N combination to compute

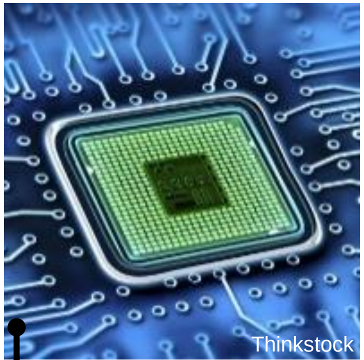
Combinatorial optimization & Ising problem

Cryptography

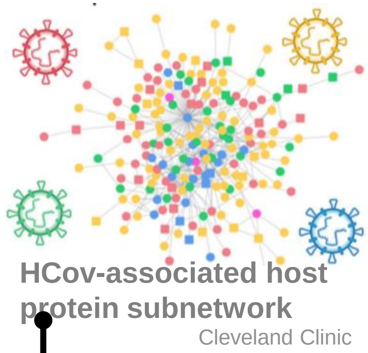
Image recognition



Circuit design



Drug discovery



Social network

Polynomial time

Exponential time

No exact solution possible with von Neumann (Heuristics or approximations used)

Mapping

Ising problem

Complexity

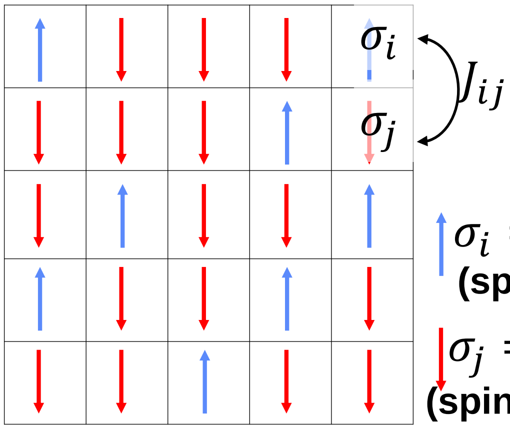
Polynomial | **NP-intermediate** | **NP-complete** | **NP-hard**

NP: Non-deterministic Polynomial (e.g. exponential)

- **Combinatorial optimization: optimization for discrete variables**
- ***If we solve Ising problem, all lower complexity problems can be solved.***

Ising problem

Ising model



$\sigma_i = +1$ (spin up)

$\sigma_j = -1$ (spin down)

Ising Hamiltonian

$$H_{Ising} = -\frac{1}{2}\sum_{\langle i,j \rangle} J_{ij}\sigma_i\sigma_j - \sum_i h_i\sigma_i$$

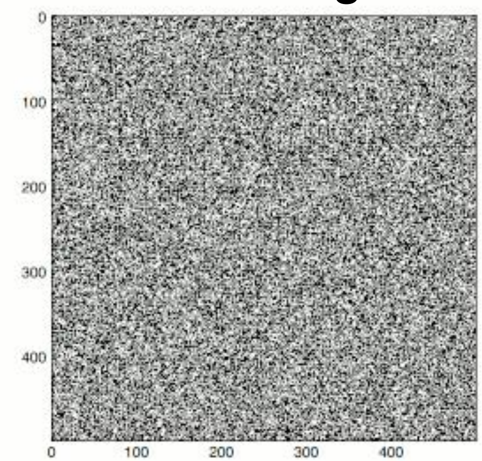
$\sigma_i \in \{-1, +1\}$

σ_i: spin state

J_{ij}: spin coupling

h_i: external field

Phase transition of ferromagnet

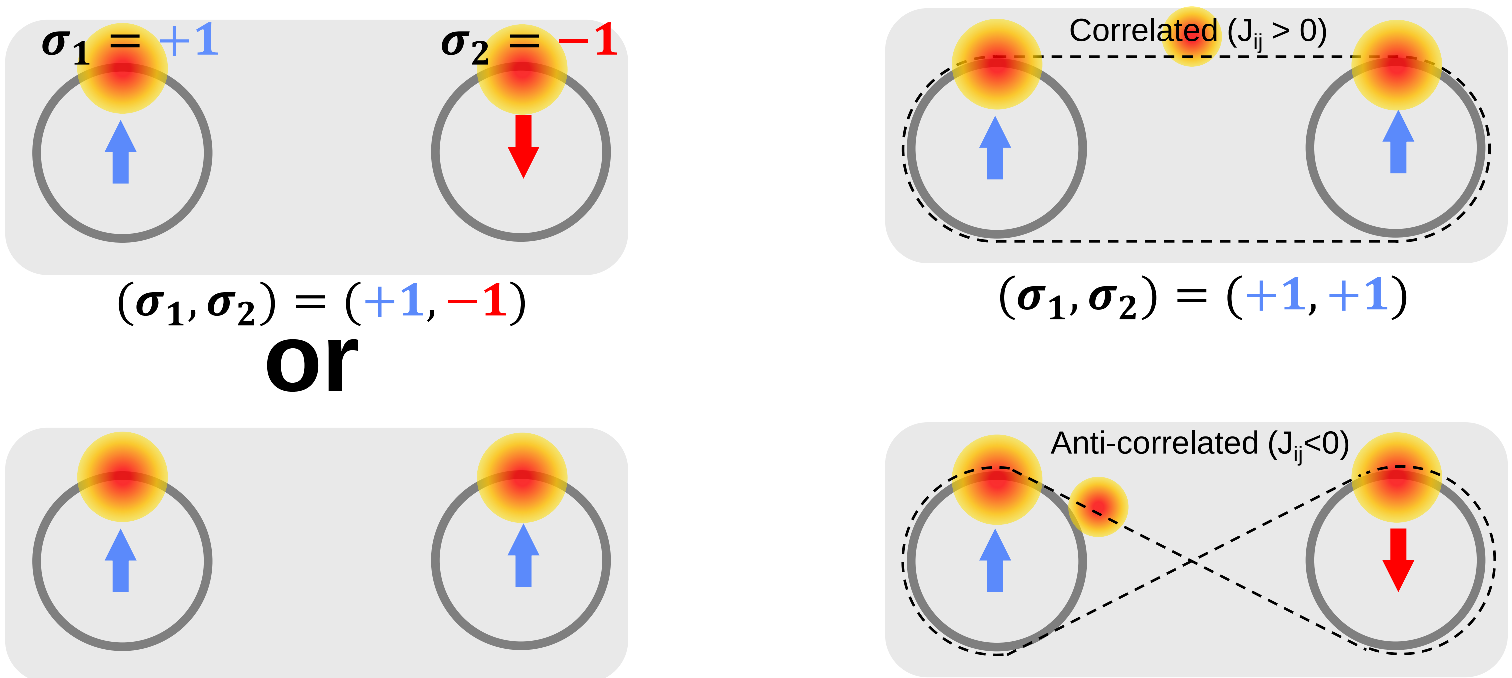


By HeMath

- **Ising problem:** `minimize H`$_{Ising}$
- **2^N possible combinations (~10^{15} combinations for 50 spins)**
- **No efficient algorithm to solve (i.e. exponential scaling)**
- **A machine mimics ferromagnets? → Ising machine**

Principle of optical Ising machine

Uncoupled lasers | **Coupled laser system**



Uncoupled lasers: $(\sigma_1, \sigma_2) = (+1, -1)$ **or** $(\sigma_1, \sigma_2) = (+1, +1)$

Coupled laser system: $(\sigma_1, \sigma_2) = (+1, +1)$ (correlated); $(\sigma_1, \sigma_2) = (+1, -1)$ (anti-correlated)

- $\sigma_{ij}(min(H_{Ising})) = \sigma_{ij}(max(Gain_{laser}))$
- **Solution (σ_{ij}) emerges spontaneously after lasing threshold**
- ***Realtime solution possible regardless of spin number***
  - $\tau_{solve} \sim \frac{1}{\Delta\nu_{cavity}}$ **(e.g. ~25 ns for 40 MHz linewidth & Q=5x10^6)**

Generalize to N spins

8-node example

Solution

$\sigma = [+1, +1, -1, -1, +1, -1, +1, +1]$

Bi-stable resonators

(spin representation)

$$v = u + S\sigma$$

Optical multiplier matrix

(Ising problem encoding)

$$W = \lambda J S^{-1}\left(I + \lambda J S^{-1}\right)^{-1}$$

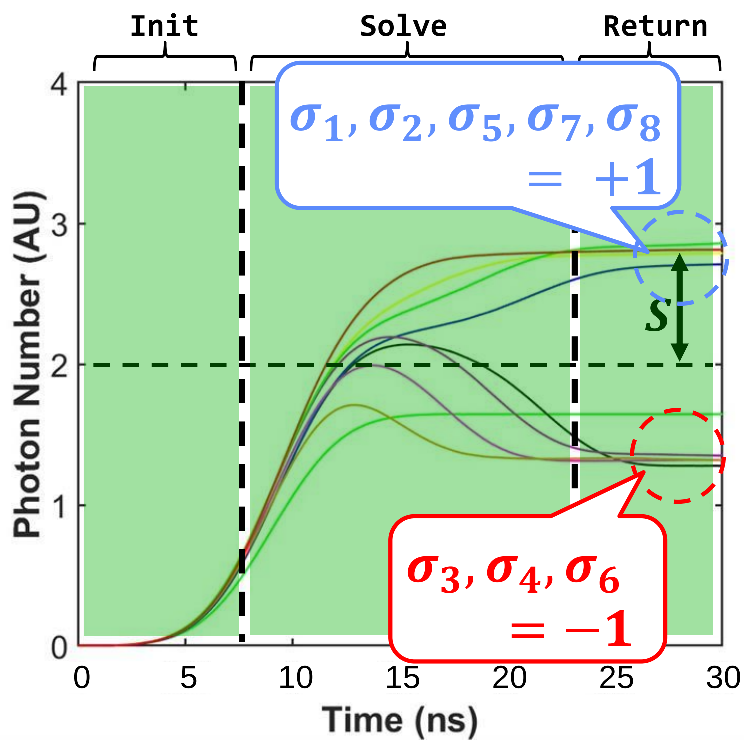
J: Ising problem (spin coupling)

S: bifurcation parameter

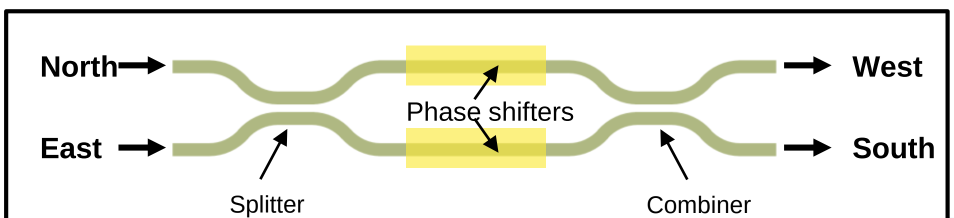
λ: proportional constant

w_{ij}

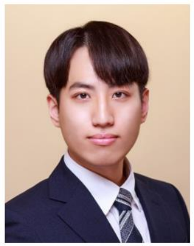
Simulation for 8 neural nodes (by co-PI)



Multiplier element (=tunable MZI)



삼성미래기술육성과제 DGIST-KAIST team



유경식 교수님

삼성미래기술센터로부터 총 14억을 지원 받아
KAIST 유경식 교수님 연구실과 함께
Ising machine (자석 방향 문제 푸는 컴퓨터)을 개발 중

서울신문 브랜드 | 신문구독 | 지면 PDF | 로그인 공식SNS채널

서울신문

서울신문 뉴스레터 지금 구독하세요

실시간 속보 김강식 경기도의원 '경기도 공동주택 공공관리제도 도입 토론회' 개최 #코인설록 #뉴스를 부탁해 | 서울신문기사 전체보기

DGIST 2020년도 하반기 '삼성미래기술육성사업' 2개 과제 선정

0 입력 : 2020-10-12 13:34 | 수정 : 2020-10-12 13:34

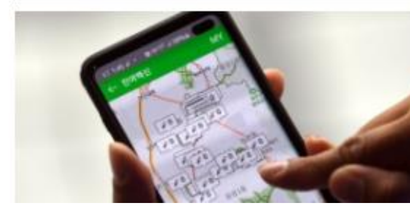
DGIST 에너지공학전공 양지웅 교수와 로봇공학전공 한상윤 교수가 삼성전자 미래기술육성사업이 지원하는 2020년도 하반기 소재기술, ICT 창의과제에 선정됐다.

가장 많이 본 뉴스 1~5 6~10

1 "반신욕하다 깜빡 잠들었다"...16시간 후 여성의 발 상태

2 손정민씨 셔츠에서 혈흔 검출...친구 옷·현장엔 핏자...
3 '돈 되면 뭐든'... 사이버 레커, 손정민 사건 낚아 수...
4 "다른 여자랑 술을 마셔?" 남친 의식불명 될 때까지...
5 술 취한 女승객, 모텔로 데려간 시내버스 기사 조사...

서울Eye : 포토뉴스 +



- **https://www.seoul.co.kr/news/newsView.php?id=20201012500072**

삼성미래기술육성사업

"

미래 과학기술을 선도할 연구자를 발굴하고,
우리의 과학기술 발전을 위해 기여하겠습니다.

지난 수 세기에 걸친 과학기술의 발전은 모든 영역에서 인간의 생활을 획기적으로 바꿔 놓았고, 최근에는 정보화 시대를 거쳐 이제 인류사회는 개방과 초연결의 시대를 맞았습니다.

일각에서는 새로운 산업혁명의 도래를 예견하는 가운데, 과연 과학기술이 어떤 방향으로 미래를 열어 갈지, 또한 그러한 변화가 드리울 그림자는 어떻게 해결할지도 새로운 과학기술의 과제가 될 것입니다.

미래 세계가 직면할 문제가 복잡하고 어려울수록 그 해결방안은 근본적인 데서 찾아야 합니다. 그러나 우리나라와 같이 선진기술을 추종하여 단기간에 선진국이 된 나라에서는 과학기술의 기초가 상대적으로 약한 것이 현실입니다. 이를 극복하여 단순히 세계 제일이 아니라 세계 최초를 가능하게 할 국가적 역량을 배양하기 위해 「삼성미래기술육성사업」이 출범한 지도 이제 7년이 지났습니다.

「삼성미래기술육성사업」은 지난 7년간 우리나라 연구개발사업의 방향을 바꾸는데 큰 기여를 했다는 평가를 국내외적으로 받고 있습니다. 연구의 가치를 결과물의 산출에 두지 않고 아이디어의 창의성과 결과의 파급력에 두는 일관된 원칙을 견지해 오고 있습니다. 과제의 선정은 최대한의 공정성을 유지하고 있고, 과제의 평가도 적극적 개입과 긍정적 환류를 기조로 하고 있으며, 무엇보다 연구자의 자율성과 자발성에 가치를 둔 연구자 중심의 개방적인 지원체계를 운영하고 있습니다.

「삼성미래기술육성사업」은 미래 과학기술을 선도할 연구자와 과제를 지속해서 발굴하고 전폭적으로 지원하여 우리의 과학기술이 한 차원 더 도약하고 밝은 미래를 열어가는 데 기여하겠습니다.

삼성미래기술육성재단 이사장 김성근

- **혁신적인 연구를 위해 삼성에서 엄격한 심사를 통해 연구주제를 선발하여 지원하는 사업 (Very prestigious)**
- **삼성미래기술육성사업 홈페이지 링크**

한상윤 교수

소속기관 대구경북과학기술원(DGIST) 로봇공학전공

분 야 ICT ◎ ICT기반 ◎ Display&Optics

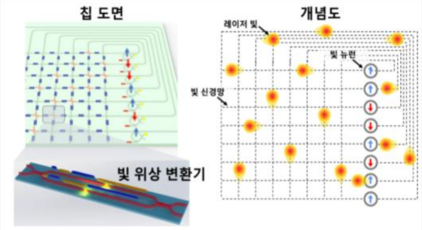
선정연도 2020년

연구실 홈페이지

조합 최적화 문제를 위한 온 칩 광학 아이징 머신

3개의 도시를 여행하는 순서는 몇가지일까요? 맞습니다, 6가지(=3x2x1)입니다. 그렇다면 10개의 도시를 여행하는 순서는? 놀랍게도 약 3백만 가지(=10x9x8...x2x1)나 됩니다. 이처럼 여러 개의 도시를 여행하는 수많은 조합들 중에서 최단경로를 찾는 것이 컴퓨터 과학의 유명한 "외판원 순회 문제" (Traveling salesman problem) 입니다. 재미 있는 점은 실생활의 많은 조합 문제들을 "외판원 순회 문제"로 바꾸어 풀 수 있다는 점입니다 (마치 컴퓨터의 모든 데이터를 0과1로 바꾸어 표현할 수 있듯). DNA 염기서열의 분석이나 택배배송의 최적화 등이 대표적인 예입니다. 따라서 "외판원 순회 문제"를 효율적으로 풀기위한 많은 노력들이 있었습니다. 하지만 도시의 수가 늘면 고려해야 할 경우의 수는 기하급수적으로 늘기 때문에 냉장고 만한 슈퍼컴퓨터들이 사용되어 왔습니다.

저희 DGIST와 KAIST합작 연구팀은 "외판원 순회 문제"를 슈퍼컴퓨터 보다 빠르게 푸는 칩을 스마트폰에 심을 수 있는 크기로 만들려고 합니다. 이 목표를 달성하기 위해 빛이 흐르는 반도체를 이용해 인공신경망을 제작할 계획입니다 (그림).



<그림. 광학 아이징 머신 칩 (빛이 흐르는 인공 신경망)>

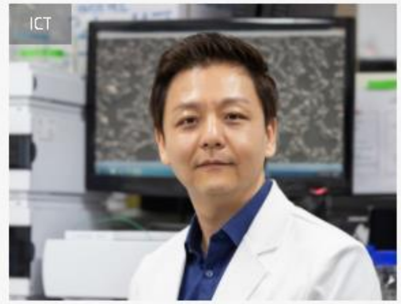
그동안 "외판원 순회 문제"를 효율적으로 풀기 위해 양자 컴퓨터를 비롯한 다양한 방식의 컴퓨터들이 제안되었지만 기존의 슈퍼 컴퓨터의 성능을 뛰어넘기는 어려웠습니다. 저희 연구가 성공한다면 자율주행차, 드론, 스마트폰 등에서 실시간으로 "외판원 순회 문제"를 풀 수 있게 되어 실생활에 많은 임팩트가 있을 것으로 기대하고 있습니다 (예: 자율주행차의 최적의 경로를 교통상황의 변화에 맞춰 실시간으로 업데이트, 스마트폰으로도 안전하게 암호화폐를 거래). 그런 날을 조금이라도 앞당기 위해 저희 연구팀은 최선을 다하겠습니다.

- **Ising machine 과제 삼성미래기술육성사업 홈페이지 링크**

주철민 교수

연세대학교 기계공학과

생체 망막 세포와 복굴절 특성의 대면적 고해상도 영상을 위한 반사형 산술 편광...



최영빈 교수

서울대학교 의과대학 의공학과

뇌종양 치료를 위한 이미지 기반 4D 이온 영동을 통한 치료나노잉크 브러싱 기술

한상윤 교수

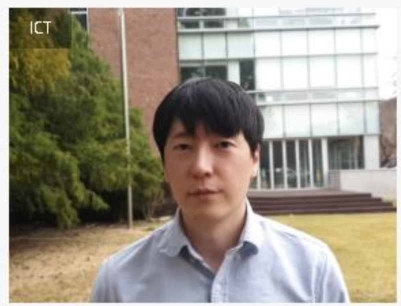
대구경북과학기술원(DGIST) 로봇공학전공

조합 최적화 문제를 위한 온 칩 광학 아이징 머신

한재덕 교수

한양대학교 융합전자공학부

250Gb/s/lane급 초고속 인터커넥트 설계 기술



황보제민 교수

KAIST(한국과학기술원) 기계공학과

강화학습을 이용한 통합된 보행 로봇 제어와 경로 탐색 체계 개발

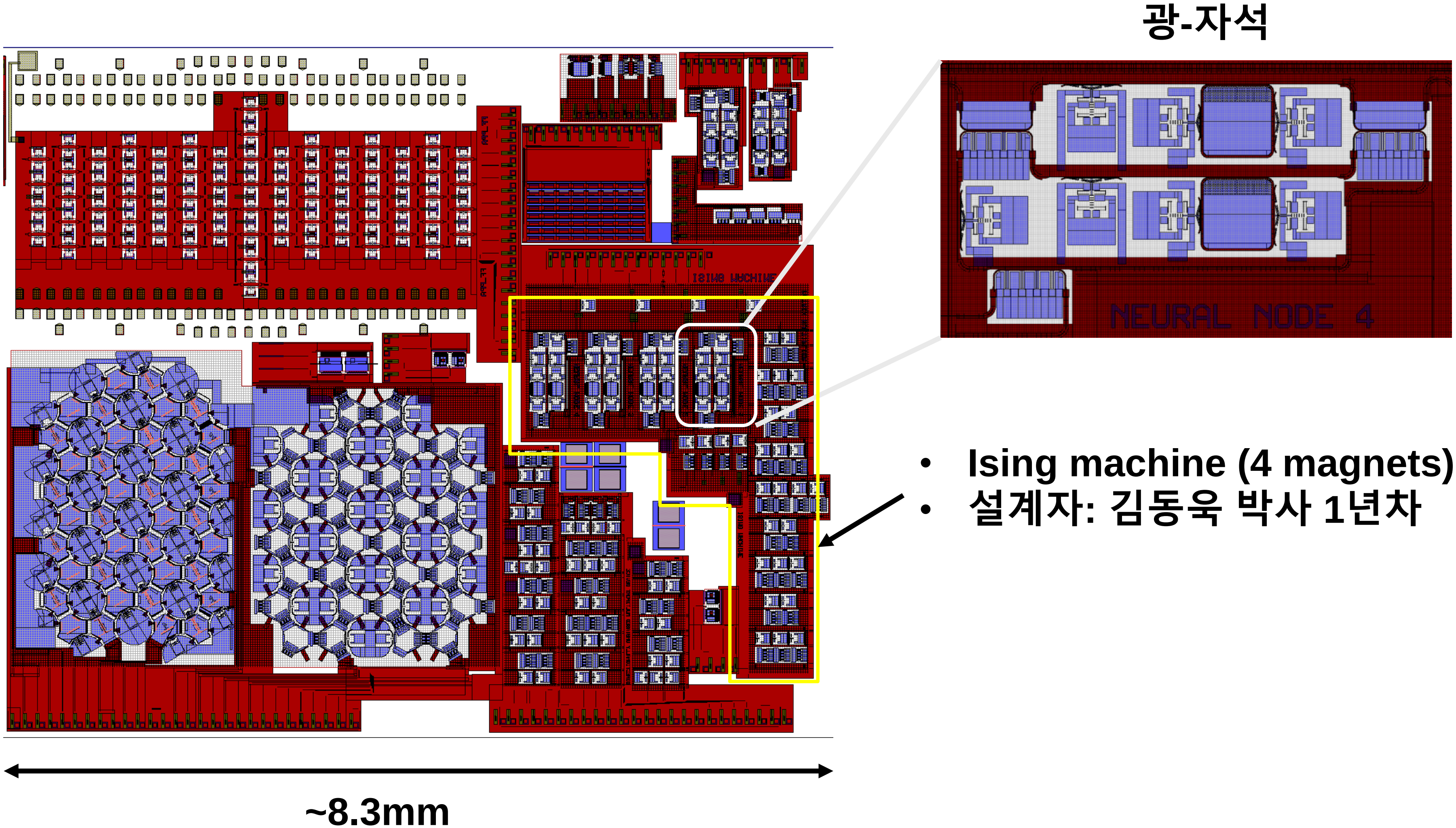
강민희 교수

성균관대학교 의료기기산업학과

다중-표적분자 동시검출용 플라즈모닉 One-pot LAMP Assay 원천기술 개발

- <u>다른 삼성미래기술육성사업 과제들 링크</u>
- **링크 따라가시면 매우 신기하고 재미있는 연구들을 보실 수 있습니다**

Ising machine 광회로 설계도 (한상윤 교수 연구실 자료)

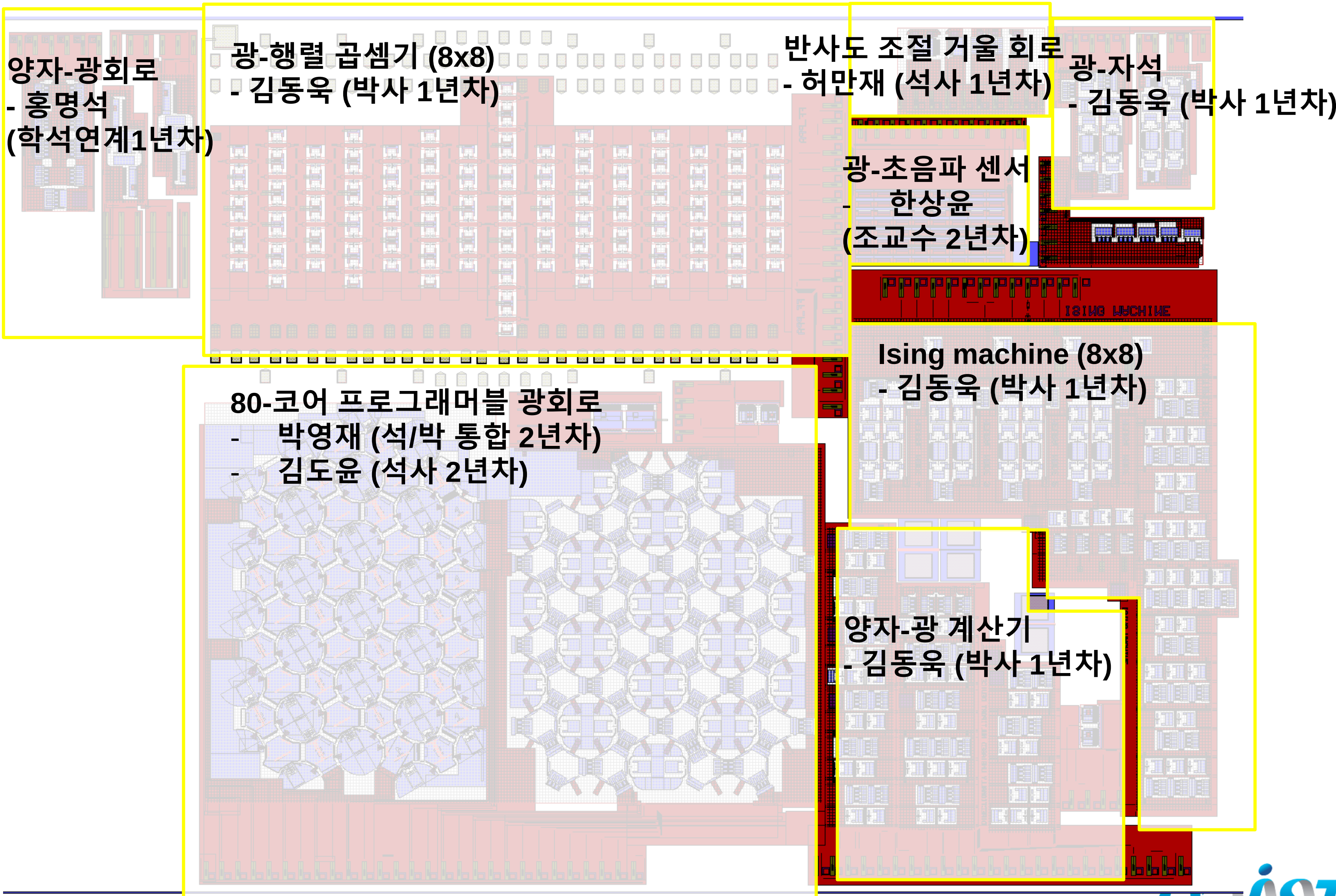


- Ising machine (4 magnets)
- 설계자: 김동욱 박사 1년차

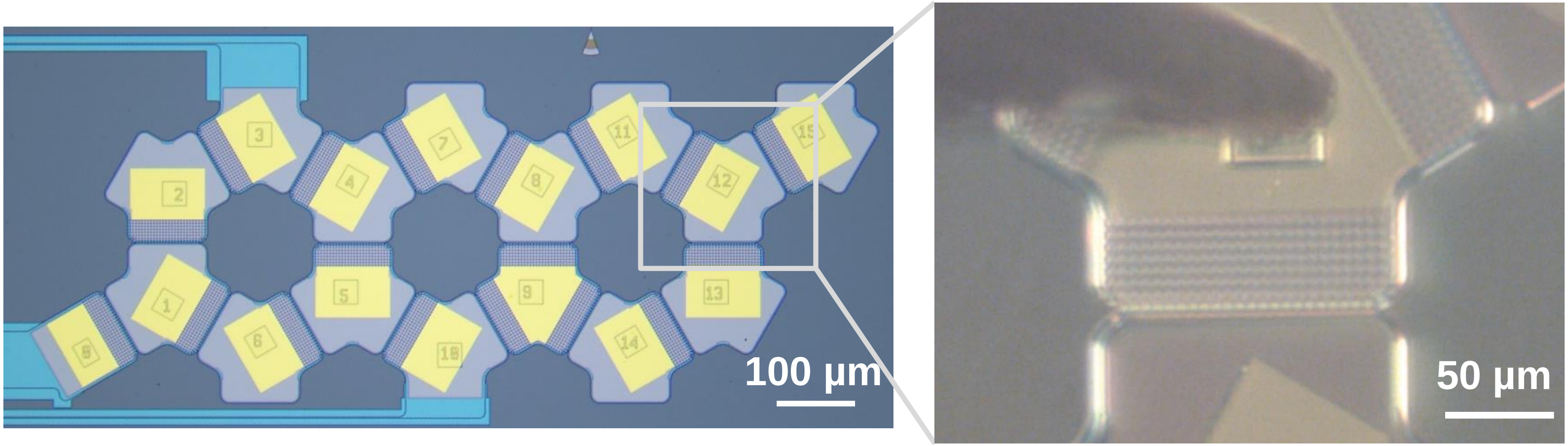
- 현재 파운드리 (반도체 공장)에서 제작 중 (8월 완료)

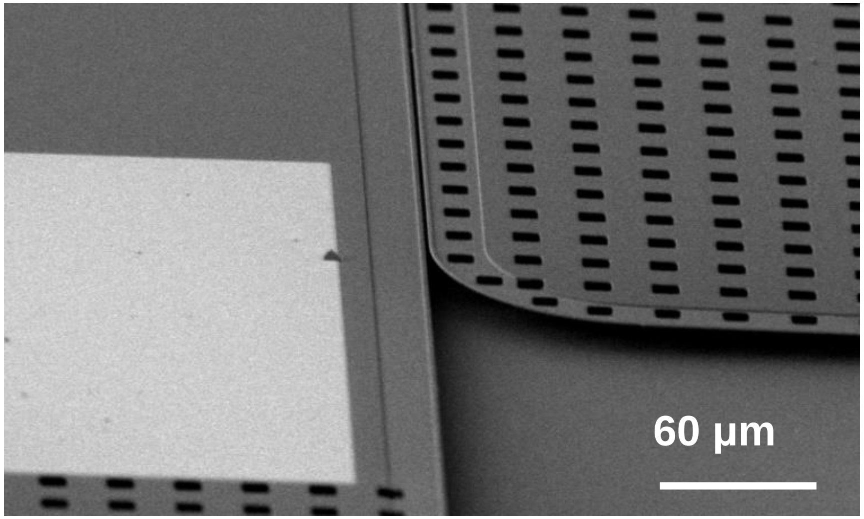
DGIST

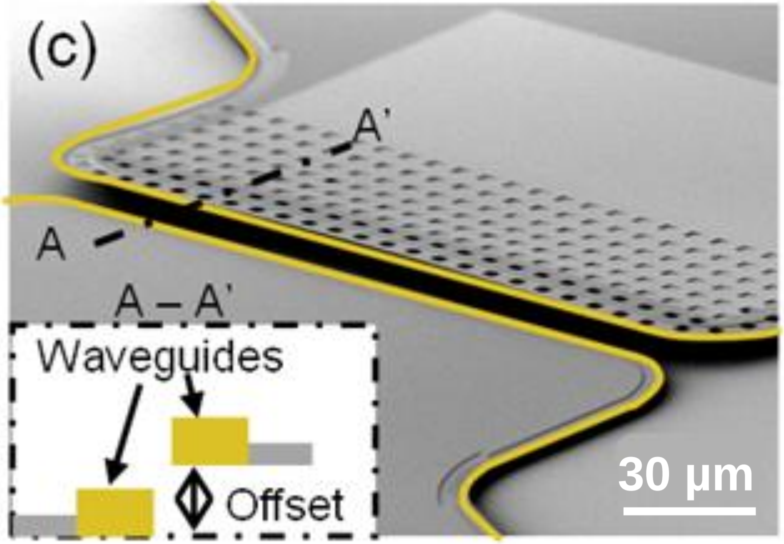
Ising machine 광회로 설계도 (한상윤 교수 연구실 자료)

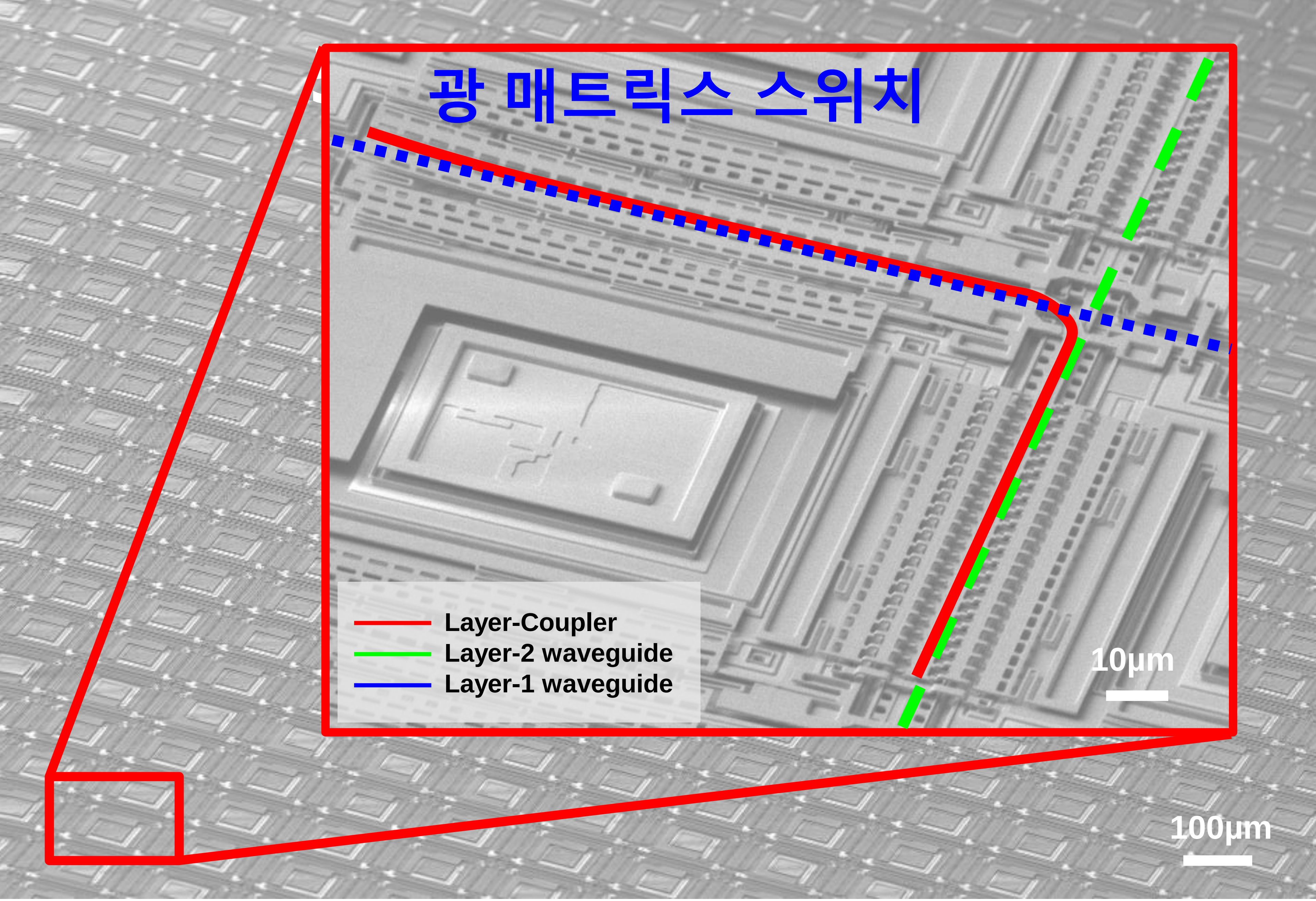


프로그래머블 광회로





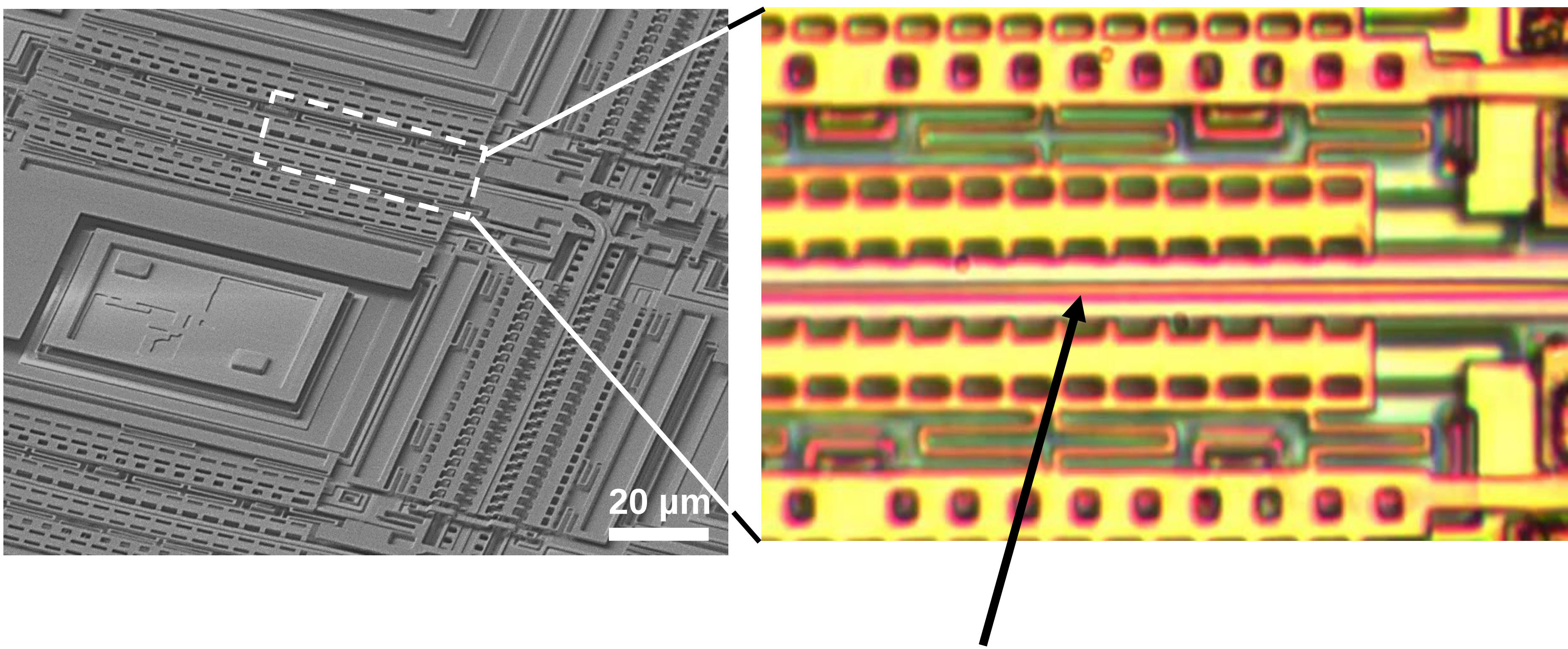




Han, Seok, Yu, Quack, Muller, Wu, JLT, 2018

Actuation video

<Unit Cell>　　　　<Coupler & Actuators>



Han, Seok, Yu, Quack, Muller, Wu, JLT, 2018

Photonics for Intelligence -Lecture 4: Quantum & Photonics (I)-

Prof. Sangyoon Han

DGIST class material

Spring 2021

200 µm

Background image: silicon photonic switch fabricated by Prof. Sangyoon Han

IST: Institute of Science & Technology

DGIST
Daegu Gyeongbuk Institute of Science & Technology

KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
KAIST
1971
한국과학기술원

UNIST
ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

GIST
광주과학기술원
Gwangju Institute of Science and Technology

- 과학기술원, 과학기술정보통신부, KIST (한국과학기술연구원)
- 과학과 기술, 이 둘은 원래부터 가까웠을까?

불과 대장간의 신 (헤파이토스)

Vulcan forging the Thunderbolts of Jupiter,
by Peter Paul Rubens, 1636


pinterest.com/pin/400046379403927149/

- **과학자로 보이지는 않죠?**

태양신, 진리의 신 (아폴로)

티에폴로 - 아폴론과 디아나

- 제가 보기엔 이분이 더 과학자 같은

기술: 경험의 학문, 과학: 예측의 학문

기술

Vulcan forging the Thunderbolts of Jupiter, by Peter Paul Rubens, 1636

- 경험적
- 만들어 내는 것 (인간을 편하게)
- 생존, 먹고사니즘….

과학

티에폴로 - 아폴론과 디아나

- 사유적, 연역적
- 우주를 이해하는 것
- 신선놀음….

대장장이 모티프

그리스/로마신화

Vulcan forging the Thunderbolts of Jupiter, by Peter Paul Rubens, 1636

2020년대 (철 남자…)

- **집단 무의식(?)속에 숨어있는 대장장이 모티프**

엔지니어는 미인을 얻는다...

그리스/로마신화

Vulcan forging the Thunderbolts of Jupiter,
by Peter Paul Rubens, 1636

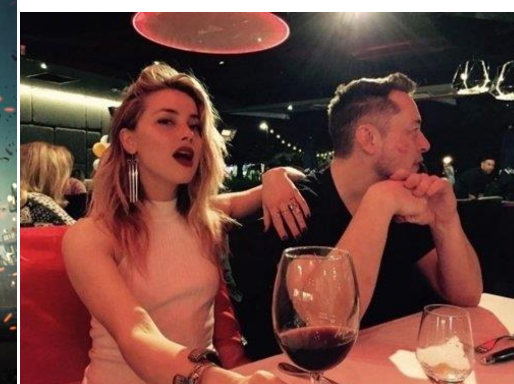
- **집단 무의식(?)속에 숨어있는 대장장이 모티프**

대장장이는 미인을 얻는다...

신화 속 세계

부부

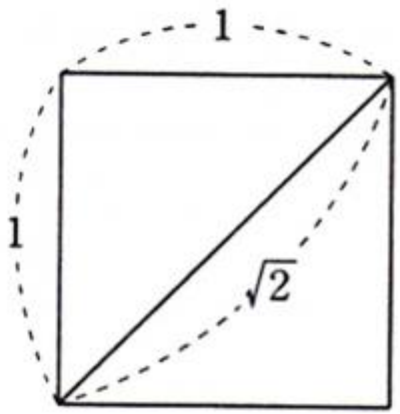
오늘날



- 오늘날에도 여전히 유효한가요?

과학은 철학적/종교적/신비주의적

$\sqrt{2}$의 비밀을 발설한 히파수스



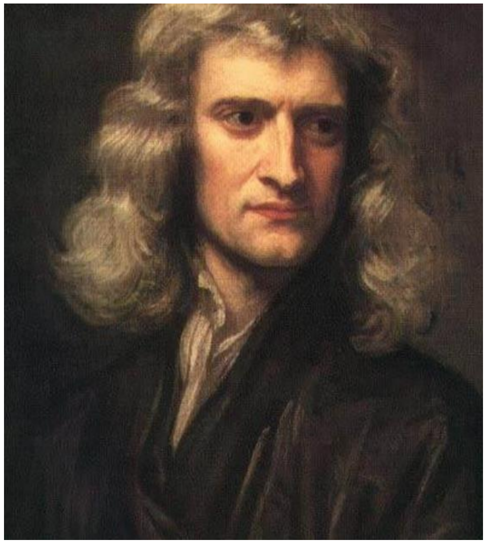
science.ytn.co.kr

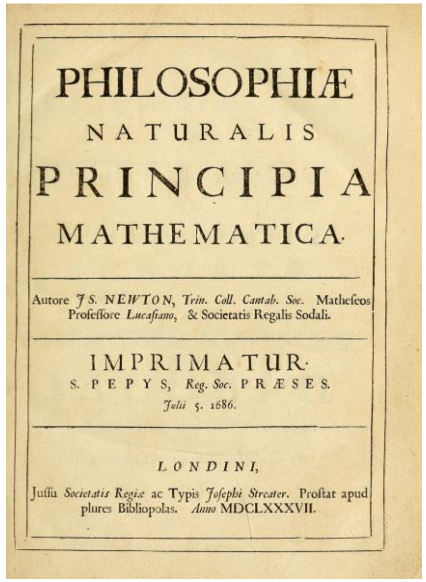
점성술 (또는 천문학?)

- 피타고라스 학파: 신비주의적, 세계를 수로 이해하려는 시도
- 천문학: 행성의 주기, 별자리, 점성학…

기술과 과학은 언제부터 친해졌을까?

뉴턴 아재
(1643~1727)





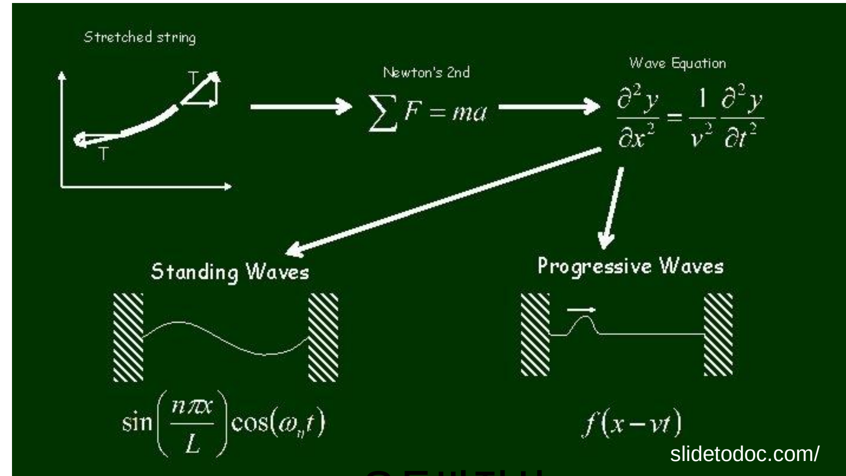
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Mathefeos Profeffore *Lucafiano*, & Societatis Regalis Sodali.

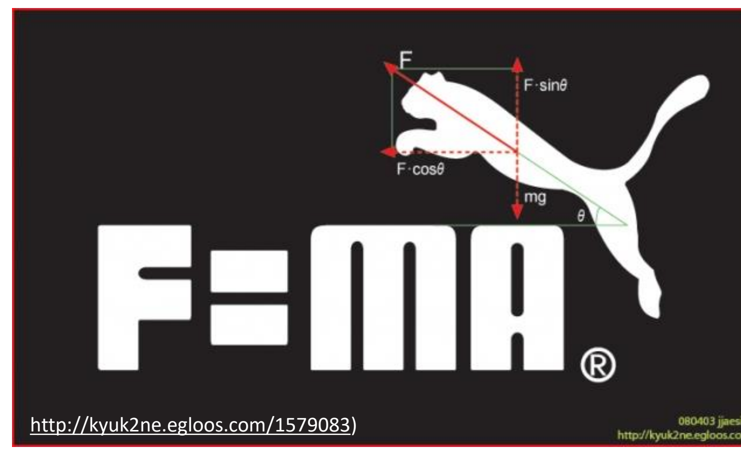
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juffu *Societatis Regiæ* ac Typis *Jofephi Streater*. Proftat apud plures Bibliopolas. *Anno* MDCLXXXVII.

기타줄의 미분방정식



운동방정식

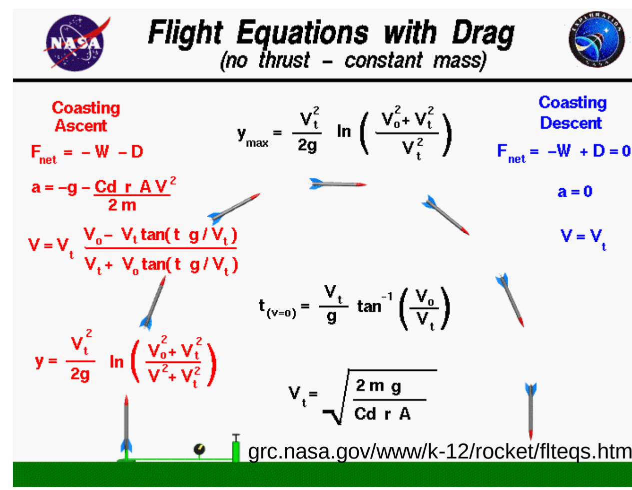


- 인간의 경험을 기술할 만큼 과학이 정교해진 시점 부터
  - 뉴턴역학, 미적분학…
- 과학혁명 (16세기): 뉴턴 (미적분)

과학을 등에 업은 기술

돌팔매
(많이 던져보는 수 밖에)

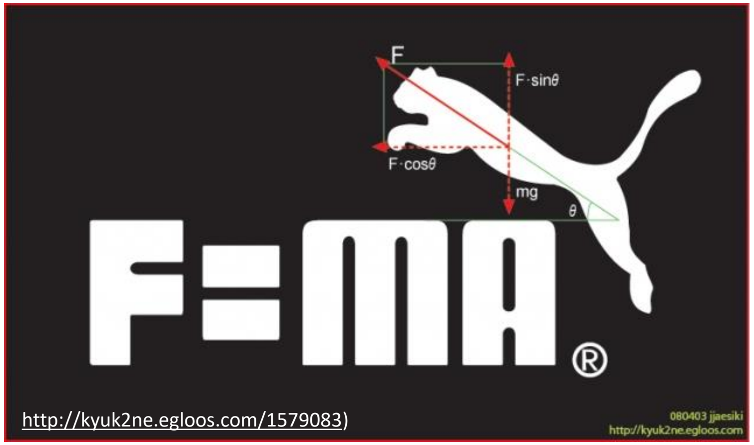
Rocket science
(쏴보지 않아도 알~아요~)



- 경험을 사유로 대체 할 수 있을 만큼 정교해진 과학

우주는 자동인형인가?

운동방정식

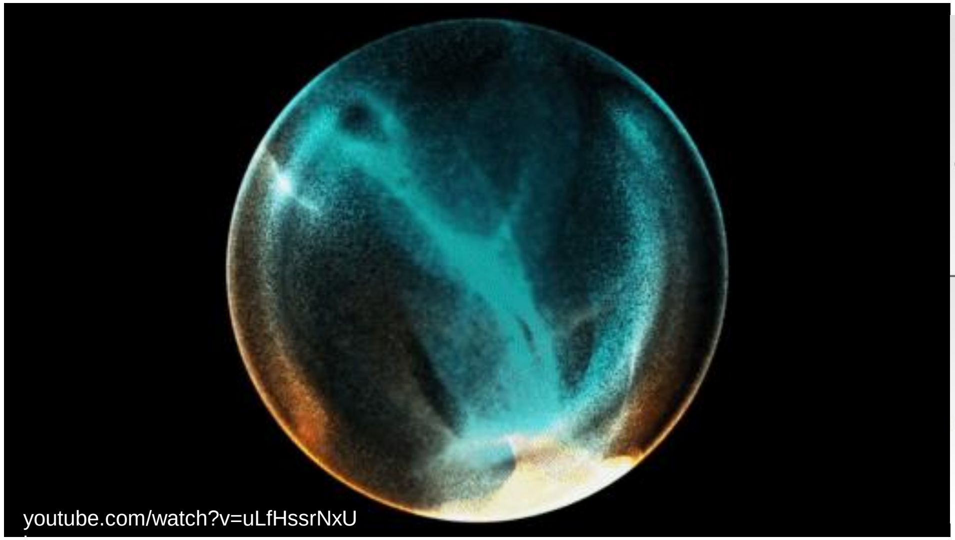


- 결정론적 세계관의 대두
  - 세상은 거대한 태엽시계, 자유의지는 환상일 뿐, 우리의 현재와 미래는 이미 과거로 부터 결정 되어있다.
  - 지배 방정식만 안다면 모든 현상을 예측 가능

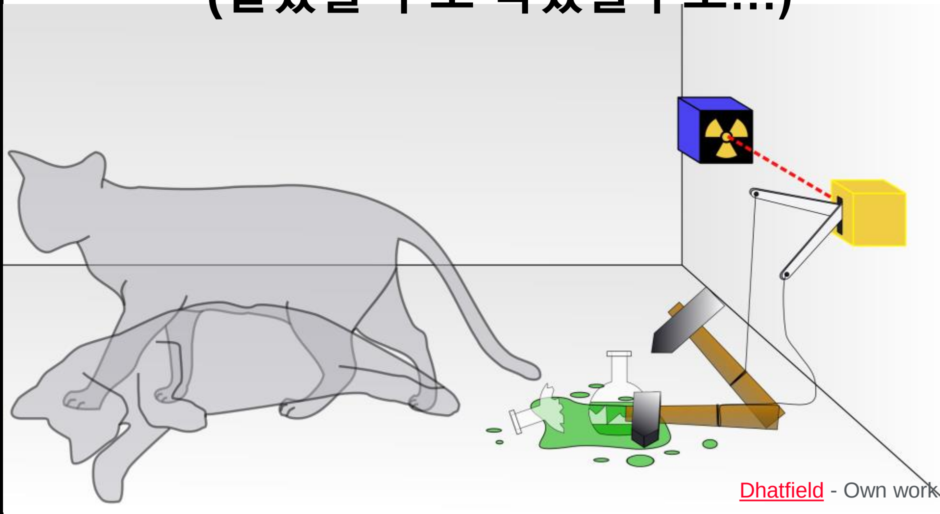
양자, 양자, 양자……, 양자!!

양자역학적 세계관

How does atom looks like?



슈뢰딩거의 냥이
(살았을 수도 죽었을수도…)



$$\left[\frac{-\hbar^2}{2m}\nabla^2+V\right]\Psi=i\hbar\frac{\partial}{\partial t}\Psi$$

- 원자의 상태는 관찰하기 전까지는 정해지지 않은 것
- 0 일수도, 1일수도
- 모르는 것이 아니라, 정말로 정해지지 않은 것
- 관찰의 순간 정해진다

Superposition principle of QM

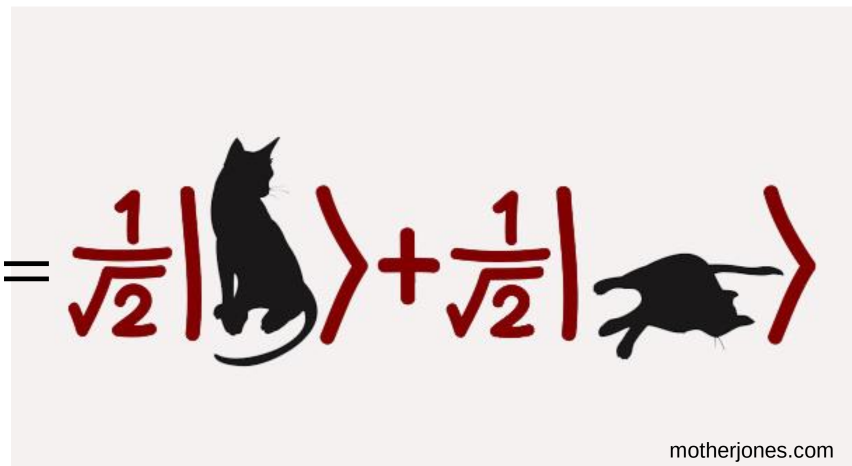
슈뢰딩거 방정식
(냥이의 운명을 가르는 식...)

$$\left[\frac{-\hbar^2}{2m}\nabla^2+V\right]\Psi=i\hbar\frac{\partial}{\partial t}\Psi$$

냥이의 상태 방정식

$$\Psi = \alpha|0\rangle + \beta|1\rangle$$

살아있는 상태　　　죽어있는 상태

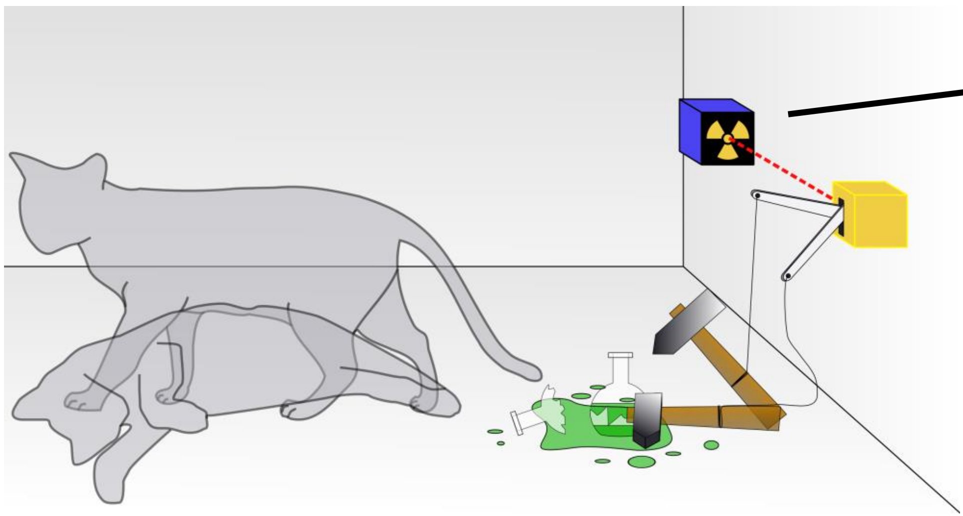
$\Psi =$ 

살아있을 확률: $|\alpha|^2$
죽어있을 확률: $|\beta|^2$

- 인간이 조작 가능한 것은 α와 β 뿐 (즉, 환경일 뿐)
- 결정은 불가능하다
- 하지만 환경을 조작할 수 있는 것이 어디냐!

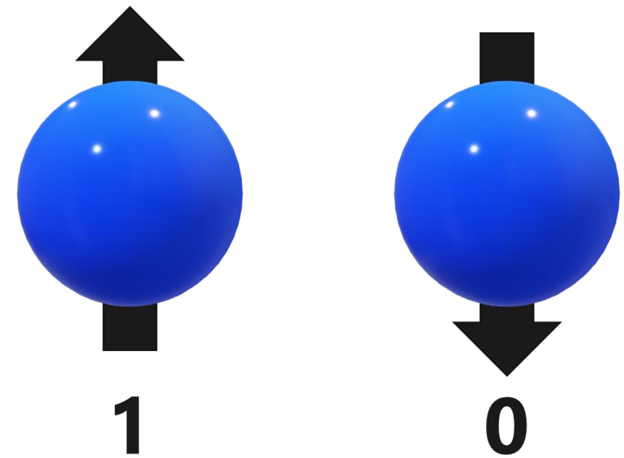
슈뢰딩거의 고양이

슈뢰딩거의 냥이
(살았을 수도 죽었을수도...)



전자의 spin

Electron Spin (Up and Down)



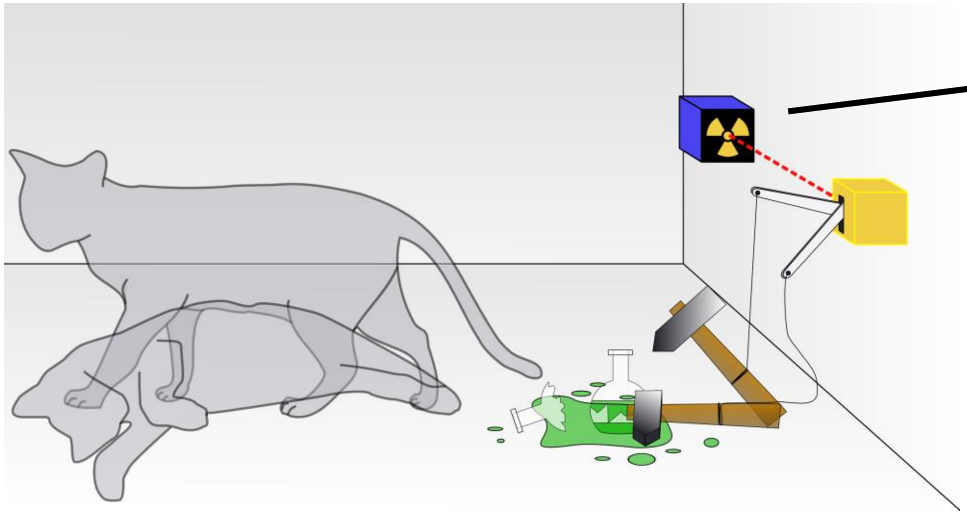
devblogs.microsoft.com

$$\Psi = \alpha|0\rangle + \beta|1\rangle$$

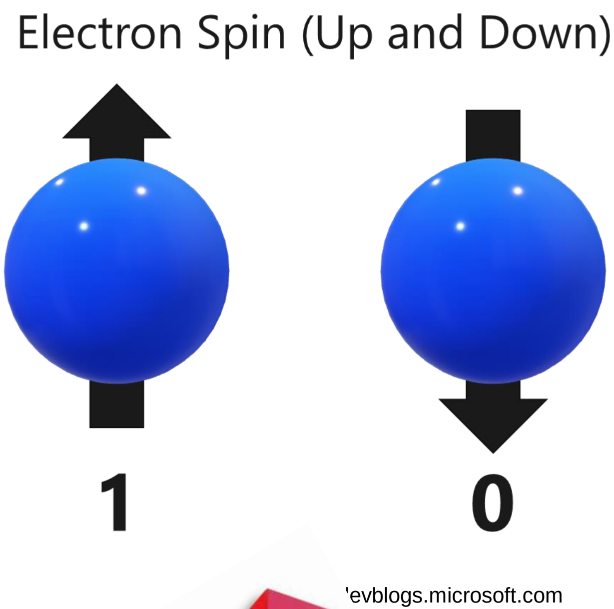
- **원자의 spin 상태에 따라 동작하는 독극물 상자**
- $|0\rangle$ **이면 독극물 살포,** $|1\rangle$ **이면 그냥 놓아둠**

고양이를 최대한 살리려면?

슈뢰딩거의 냥이
(살았을 수도 죽었을수도…)

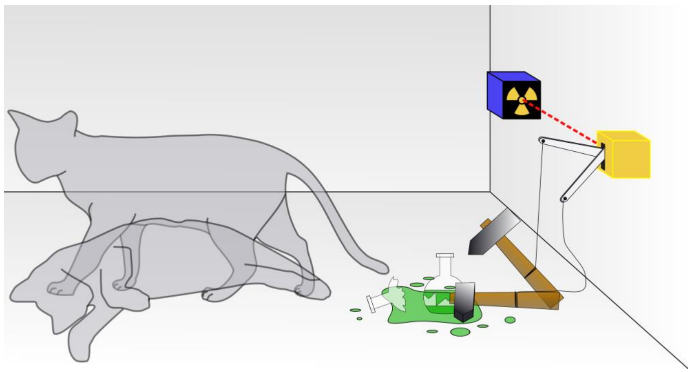


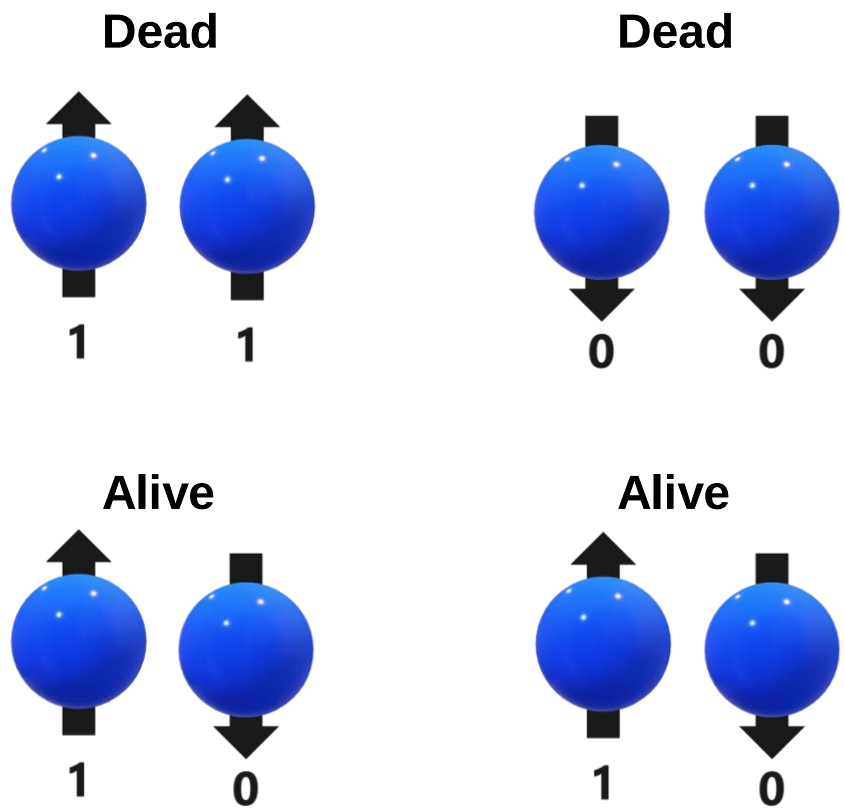
전자의 spin



- 원자 근처에 자석을 가까이 하면 살릴 수 있는 확률이 높아진다!
  - = 환경의 조작
- 100% 는 아니지만

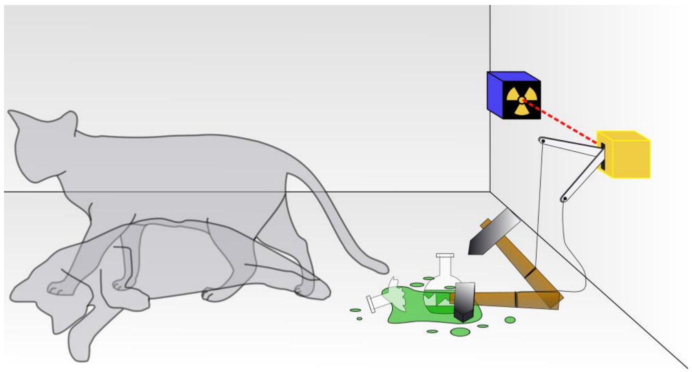
새로운 독극물 상자 upgrade!

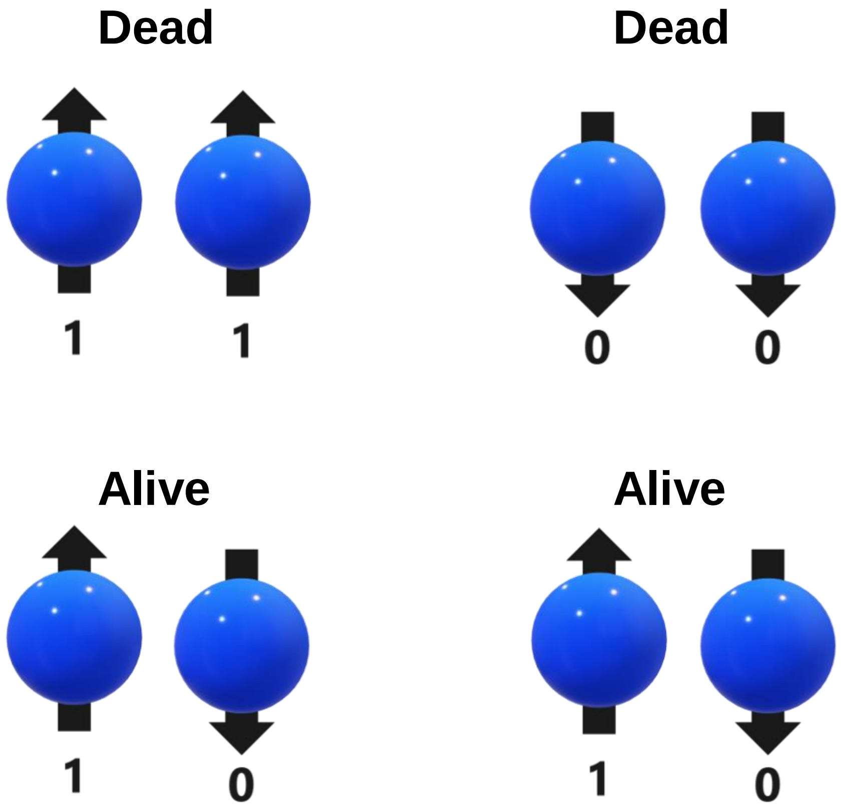




- 2개의 전자를 사용
- 서로 같은 방향을 가리킬때만 독극물 살포!
- Pop quiz: 자석의 방향이 random 이라면 고양이가 살 확률은?

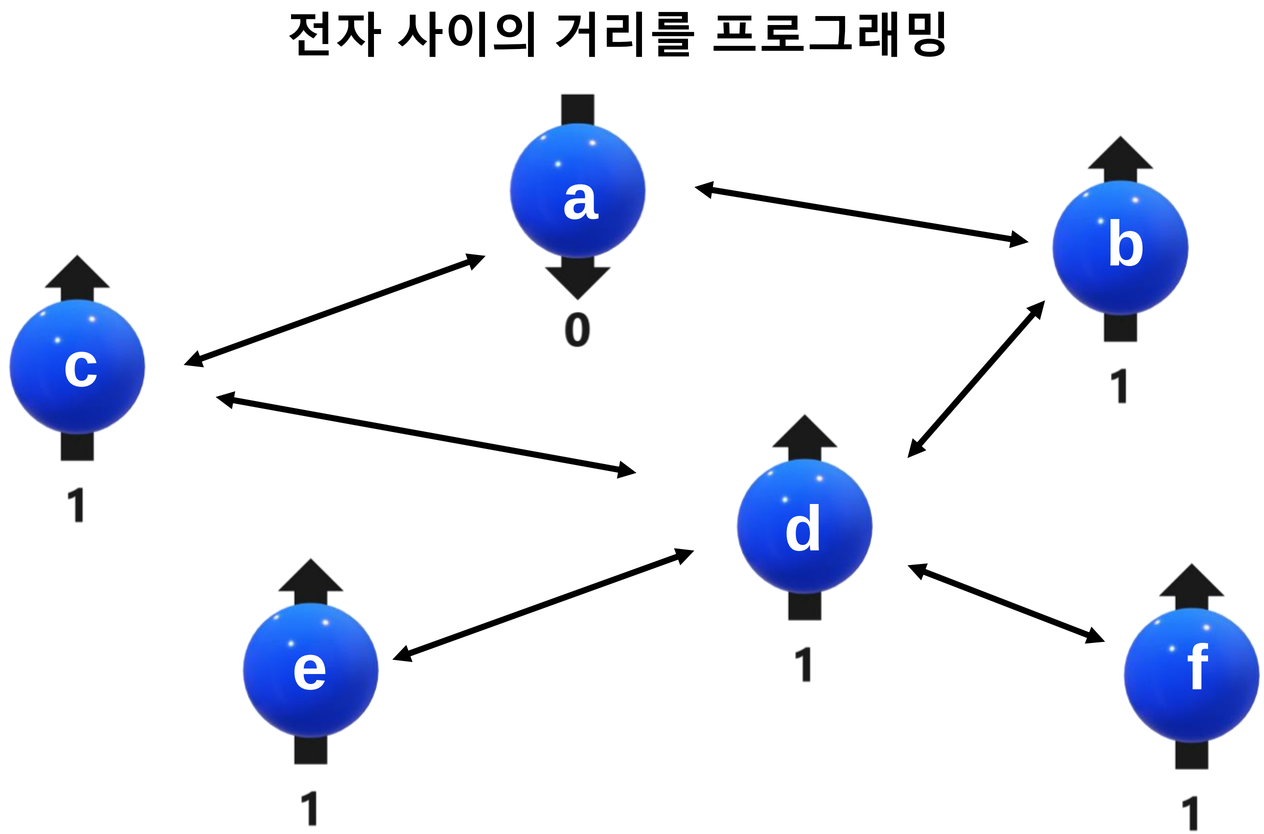
만약 두개의 전자가 가까이 있다면?





- 서로 반대방향으로 정렬하려고 하는 경향 생김 (자석과 동일)
- 전자가 가까울수록 고양이는 더 살 확률이 커진다!

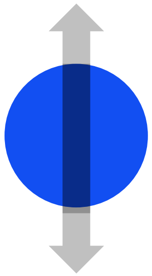
양자 컴퓨터의 원리



- 양자컴퓨터는 어떤 시스템의 확률을 계산하는 것
- 인간은 시스템(예: 전자사이의 거리)을 조작 한다

Qubit (quantum bit)

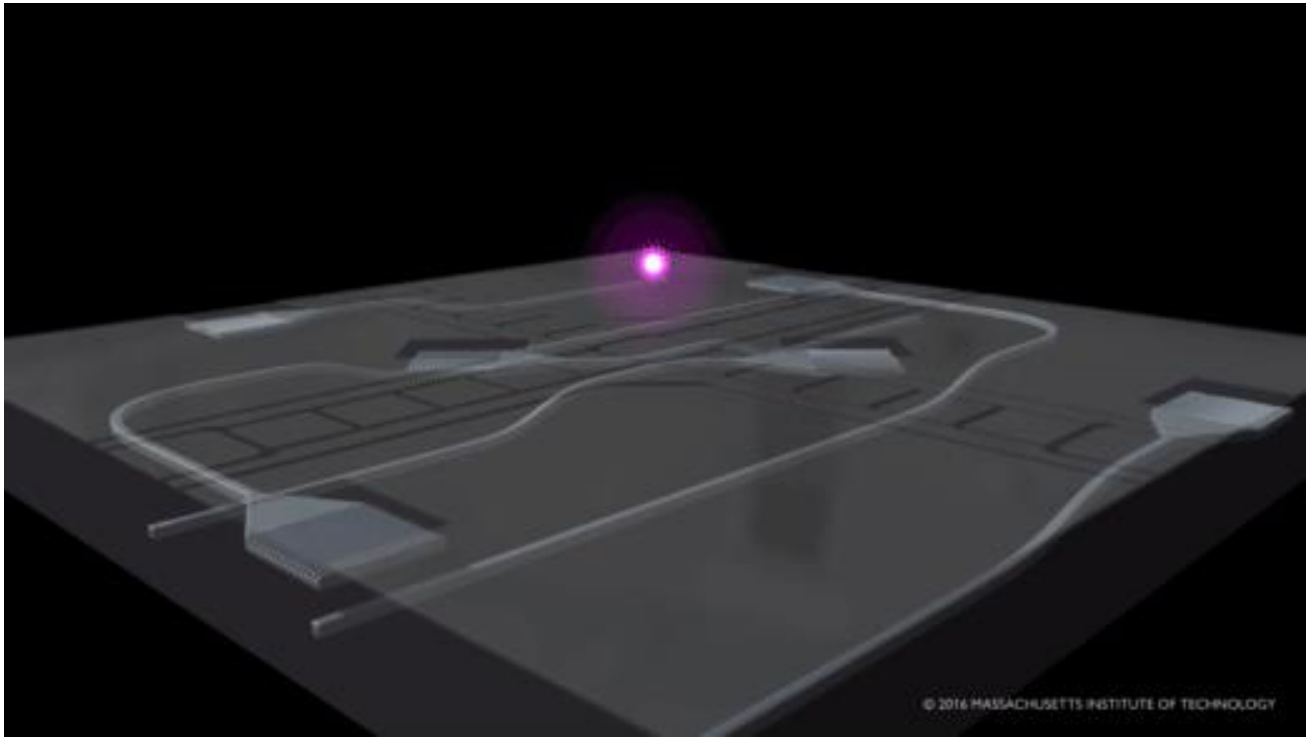
Qubit
(이것은 0도 아니고 1도 아니여...)



Bit (classical)
(0은 0이고 1은 1이니...)

- Qubit ≈ 동시에 여러 상태를 가질 수 있는 bit
- 원자에너지 준위, 전자 스핀, 광자 편광 등등

이 동영상 기억나시나요?

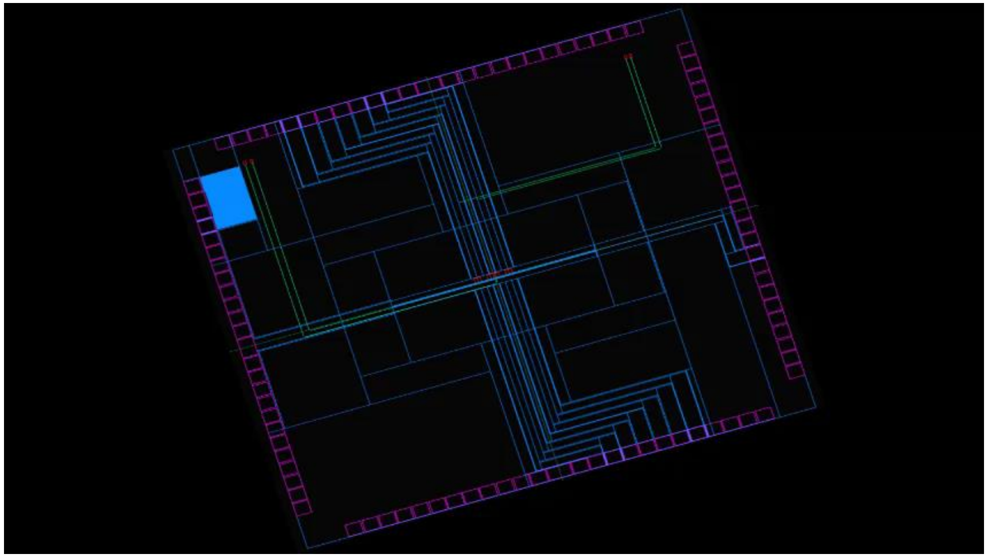


https://www.youtube.com/watch?v=UT3ev9OgkmY

- **Trap single ion (yes, single ion) with electric field**
- **Turn ion on/off using light**

양자 컴퓨터 ≈
전자(원자)를 가지고 하는 주판알 놀이

양자 컴퓨터



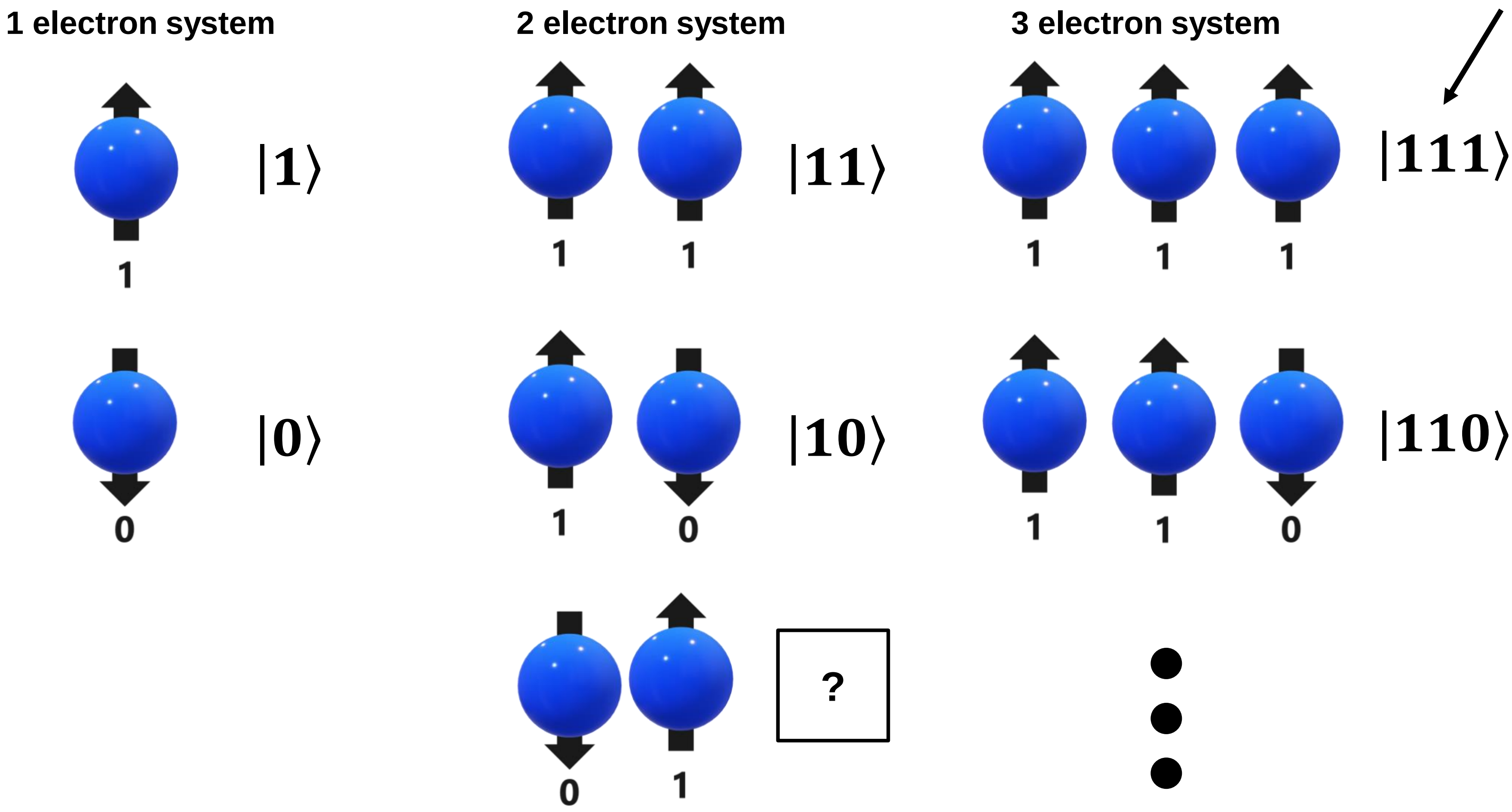
Mehta, K., Bruzewicz, C., McConnell, R. *et al.* Integrated optical addressing of an ion qubit. *Nature Nanotech* **11,** 1066–1070 (2016)

주판

- **생긴 것도 비슷하네.....**

Ket notation

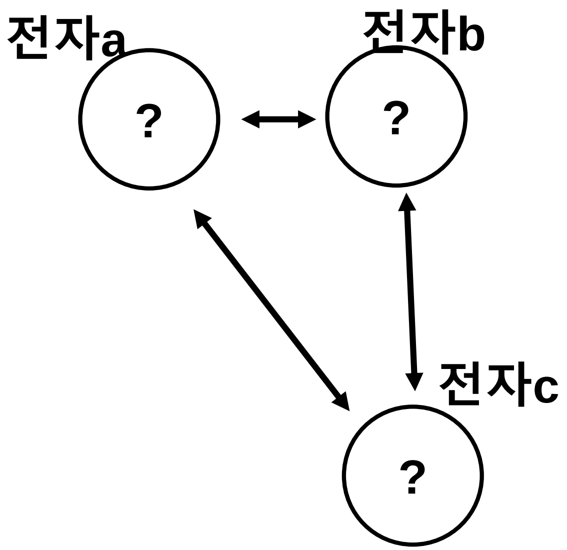
State of system
(Ket)



- **Pop quiz: how many states in 4 electron system?**

양자 컴퓨터의 원리

전자 사이의 거리를 프로그래밍 ⇔ α 들을 조절하는 것



a b c　　a b c　　a b c

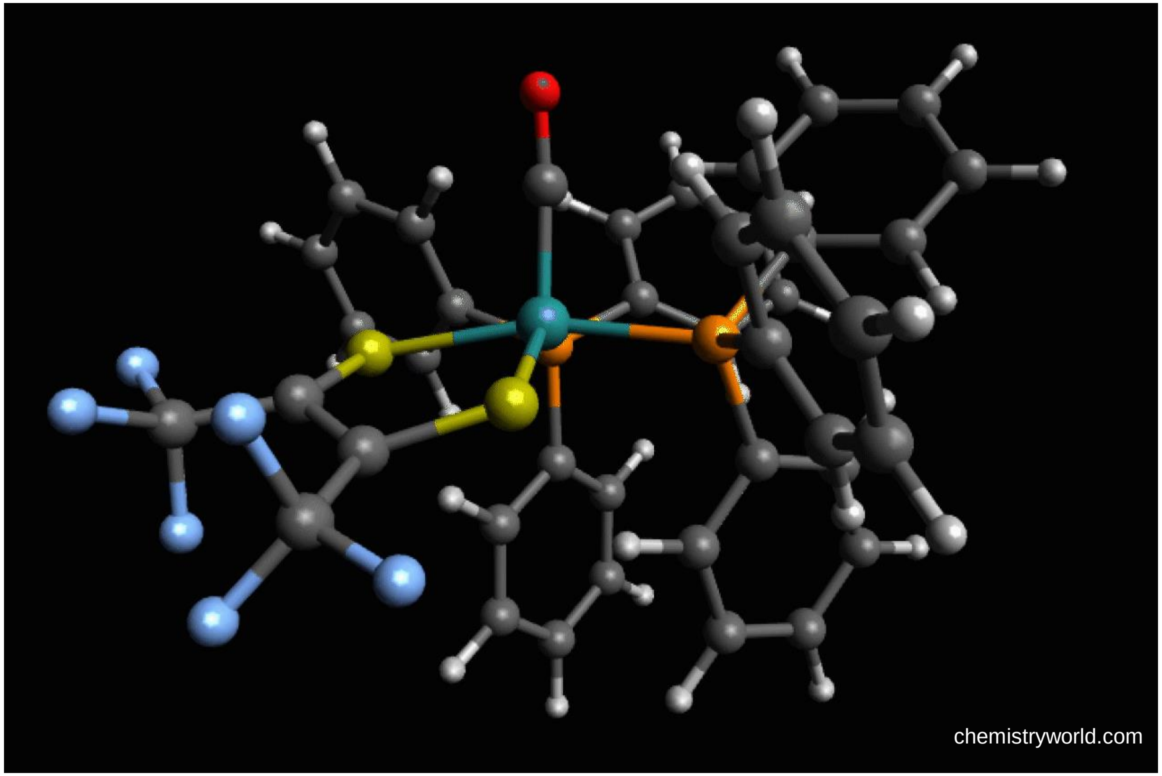
$$\Psi = \alpha_{000}|000\rangle + \alpha_{001}|001\rangle + \alpha_{011}|011\rangle \;\ldots.$$

- **Pop quiz: 여기서 α들이 의미 하는 것은?**

여기서 잠깐!

- 모든 원자들이 양자역학적(=확률적)으로 동작한다면 이 세계는 왜 대부분 예측 가능할까?

Molecule illustration



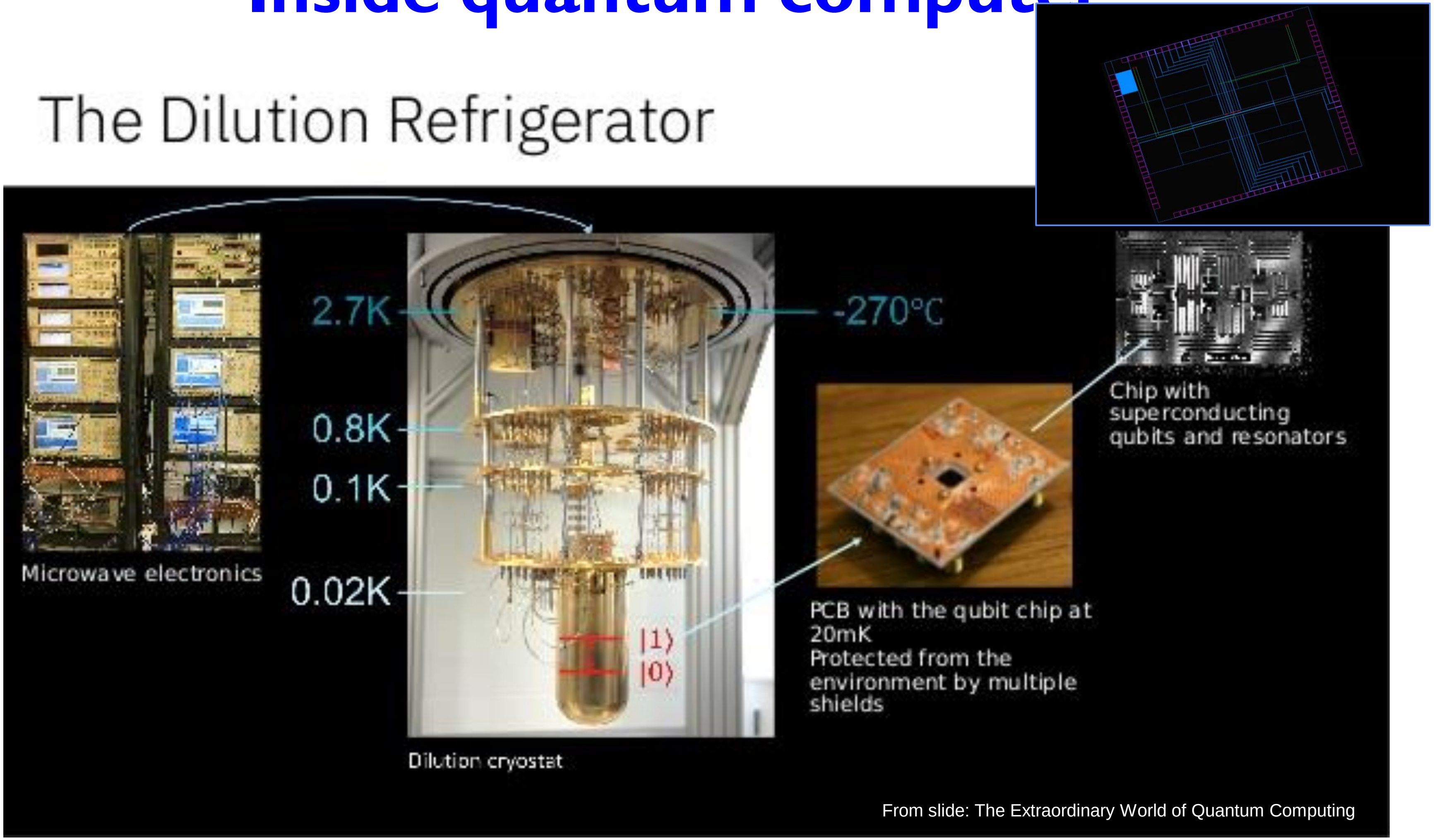
$$\Psi = \alpha_{000\ldots}|000\ldots\rangle + \alpha_{001\ldots}|001\ldots\rangle + \alpha_{011\ldots}|011\ldots\rangle \ \ldots.$$

양자 컴퓨터 사진

Feat: Sundar Pichai (AKA. CEO of Google)

- **원자 (전자)가지고 계산하는데, 양자 컴퓨터는 왜 이렇게 커??**

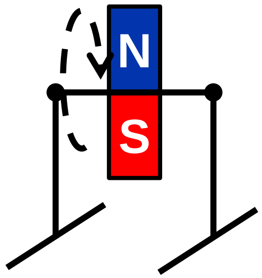
Inside quantum computer



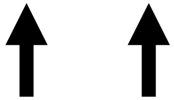
- 원자들 끼리만 상호작용하려면 극저온, 초진공 환경이 필요

자석 방향 문제 (유사해 보이나요?)

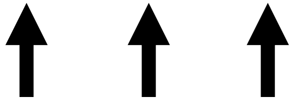
Free to rotate



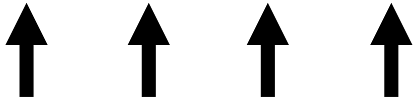
2 magnets



3 magnets



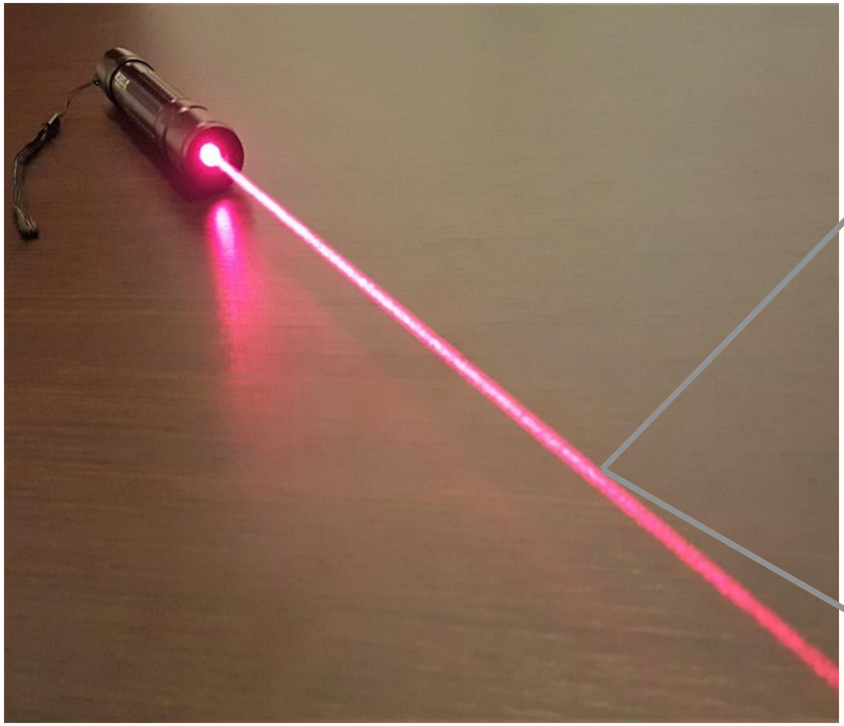
4 magnets

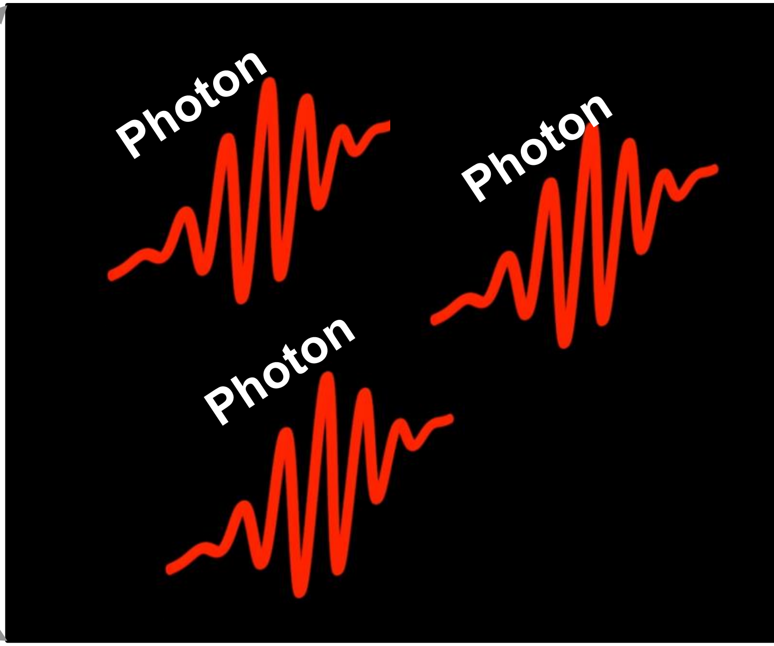


- It is a NP-hard problem
- N magnets → 2^N combination to compute
- Can also be solved with

Optical quantum computer

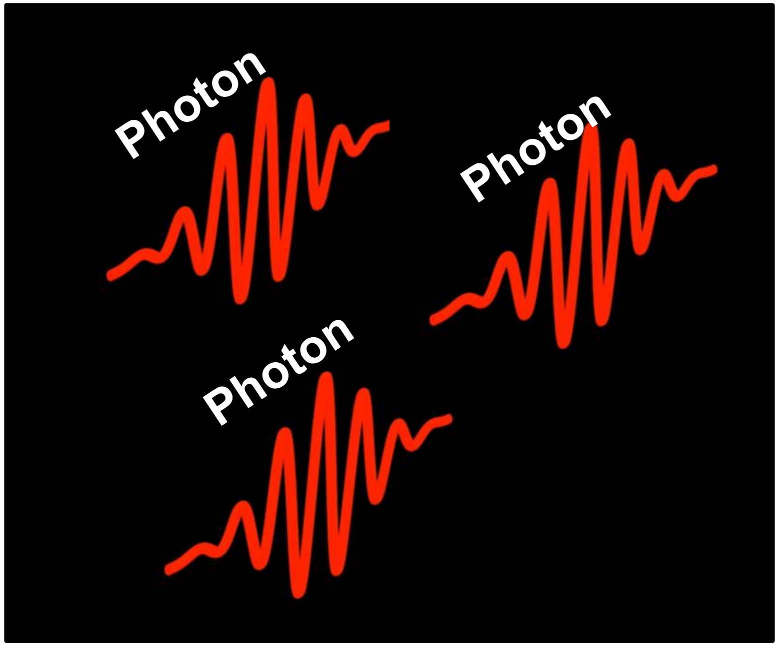
빛도 양자 역학적인 시스템이다 (당근이지)





- 빛의 세기를 줄이고 줄이면 광자 (photon)이 된다
  – 광자: 더 이상 쪼갤 수 없는 빛의 기본 알갱이
- 마치 물질을 쪼개고 쪼개면 원자 (전자)가 되듯이

Photon as a qubit



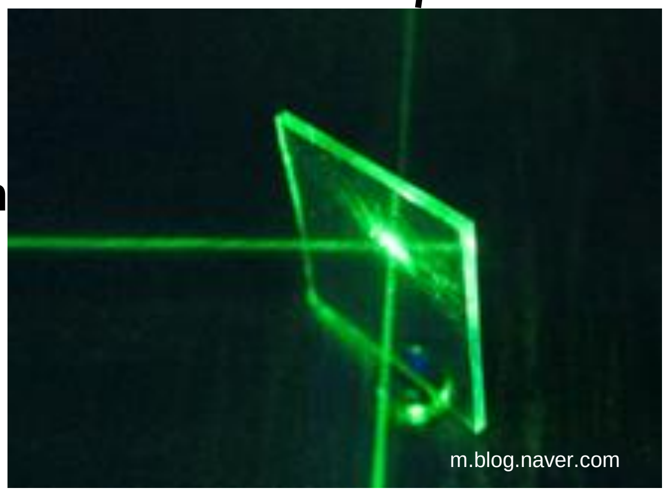
- 광자도 qubit 으로 사용 가능하다
- 여러가지 성질을 사용 가능: 위치, 편광, 모드 등등

Photon as a qubit

50:50 beam splitter

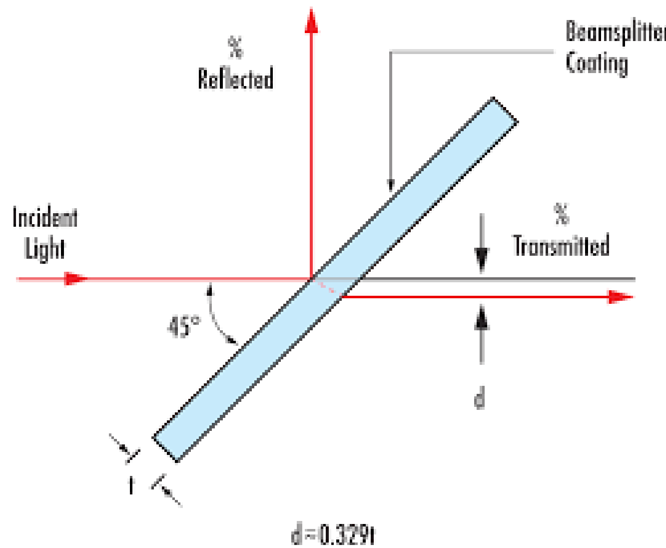
Out

Reflection



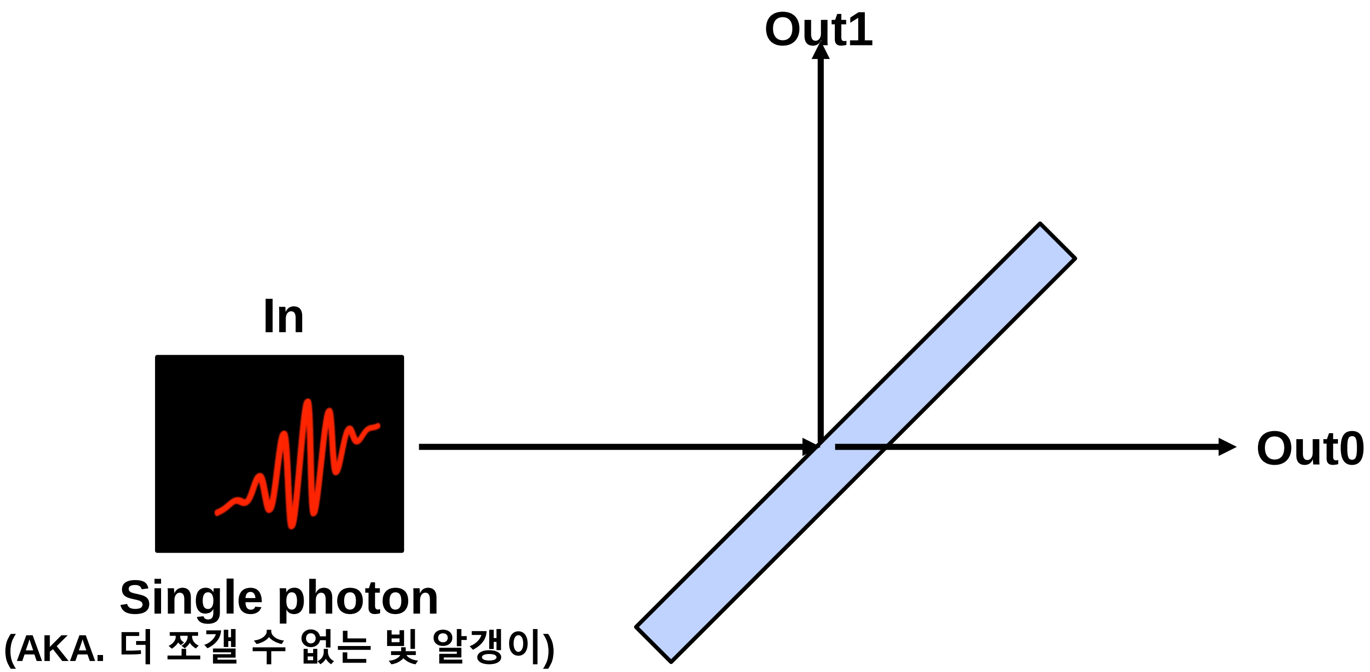
In

50:50 beam splitter



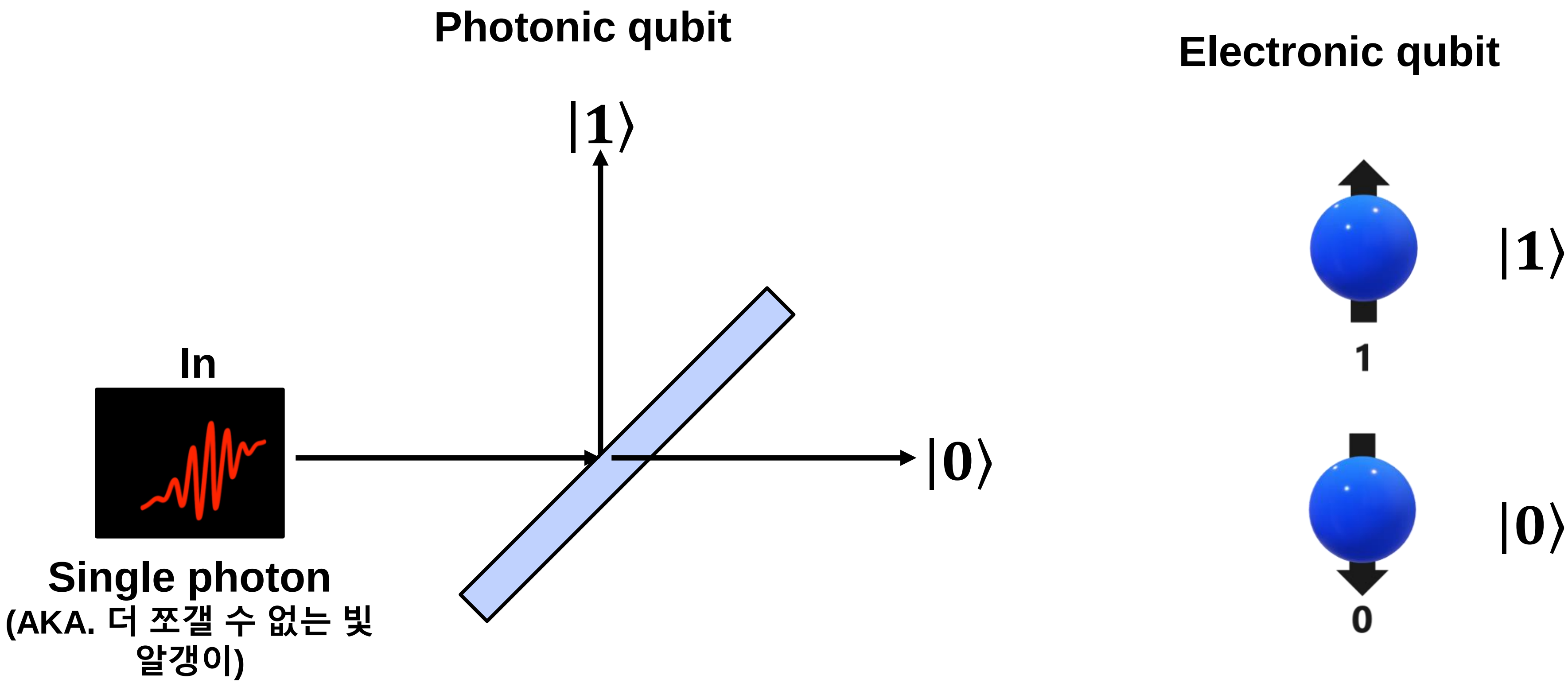
- **50:50으로 빛을 나눠주는 유리 (예: 슬라이드 글라스)**
- **만일 In 에 하나의 광자가 들어간다면?**

Single photon transmitting through beam splitter

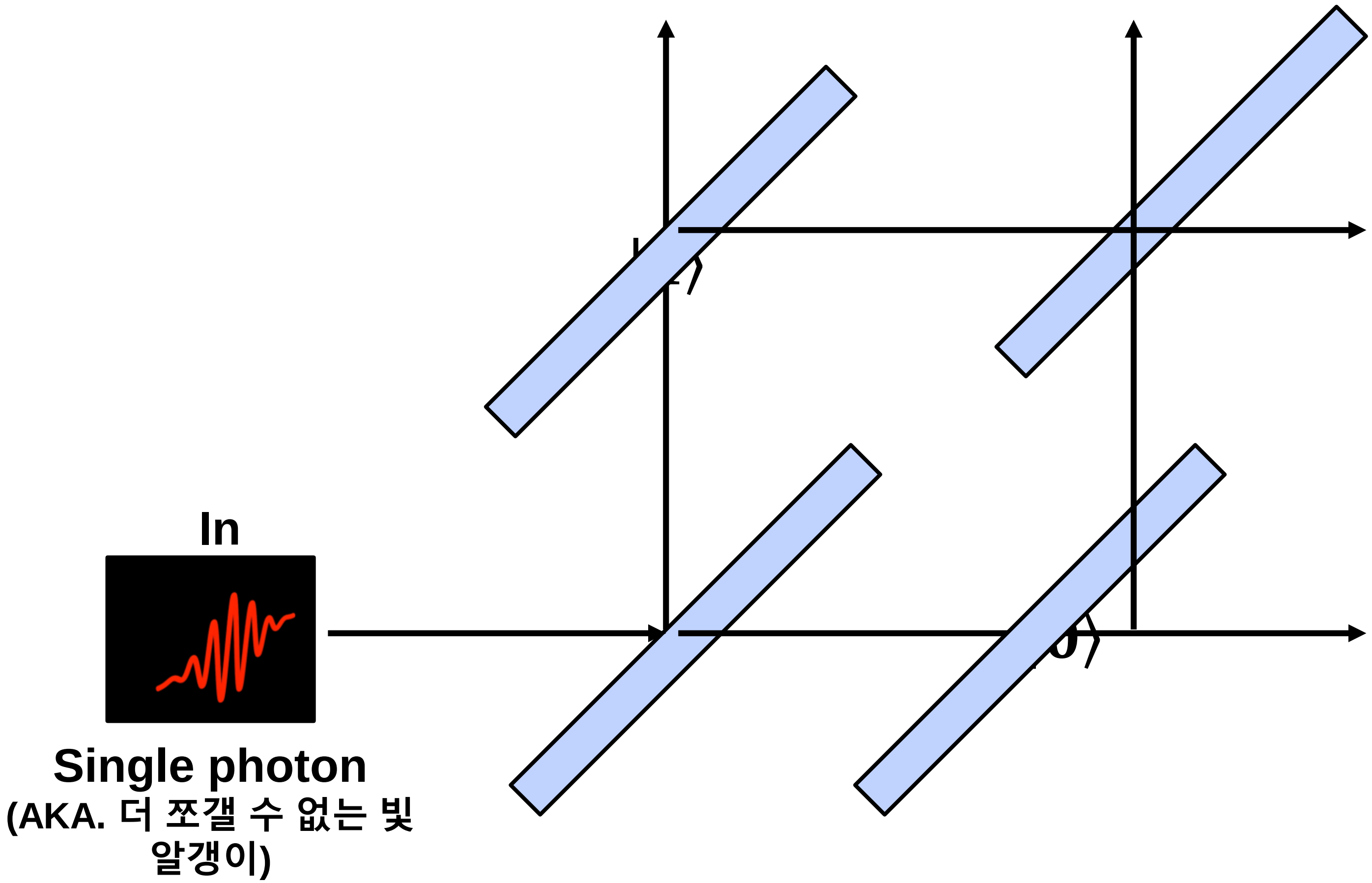


- Pop quiz: photon은 어디로 갈까요?
  - 1) out0
  - 2) out1
  - 3) 알수 없다

Single photon transmitting through beam splitter



How to make a photonic quantum computer?



Photonics for Intelligence -Lecture 5: Quantum & Photonics (2)-

Prof. Sangyoon Han

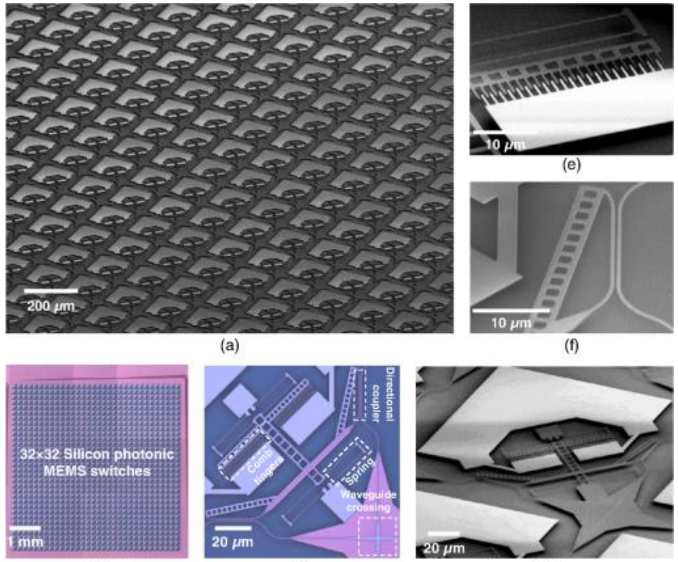
DGIST class material

Spring 2021

200 µm

Background image: silicon photonic switch fabricated by Prof. Sangyoon Han

SPIE JOM 표지논문 선정 (2021년 4월)



(a) (e) (f) (b) (c) (d)

32 × 32 silicon photonic MEMS switch with gap-adjustable directional couplers fabricated in commercial CMOS foundry

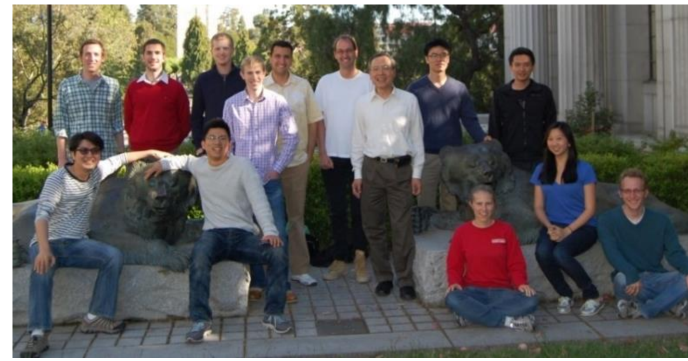
Sangyoon Han,[a,b,†] Jeremy Beguelin,[b,c,†] Lane Ochikubo,[d] John Jacobs,[d] Tae Joon Seok,[b,e] Kyoungsik Yu,[b,f] Niels Quack,[b,g] Chang-Kyu Kim,[b,h] Richard S. Muller,[b] and Ming C. Wu[b,*]

[a]Daegu Gyeongbuk Institute of Science and Technology, Department of Robotics Engineering, Daegu, Republic of Korea
[b]University of California, Berkeley, Department of Electrical Engineering and Computer Sciences, Berkeley, California, United States
[c]SUSS MicroOptics SA, Hauterive, Switzerland
[d]TSI Semiconductors, Roseville, California, United States
[e]Gwangju Institute of Science and Technology, School of Electrical Engineering and Computer Science, Gwangju, Republic of Korea
[f]Korea Advanced Institute of Science and Technology, School of Electrical Engineering, Daejeon, Republic of Korea
[g]Institute of Microengineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[h]Korea Polytechnic University, Department of Nano and Semiconductor Engineering, Siheung, Republic of Korea

- DGIST, UC Berkeley, EPFL, KAIST 공동연구
- 데이터센터의 서버 간의 통신 대역폭을 획기적으로 늘릴 수 있는 기술
- 상용 파운드리에서 생산 테스트 성공!
  - 제품화를 위한 매우 중요한 스텝

Graduate School

- **Corning Outstanding Student Paper Competition, 2014**
  - 미국 코닝사 후원 학생 논문 경진 대회
  - **Finalist (341개 논문 중 상위 6개 선발)**
- **Collegiate Inventors Competition, 2015**
  - 미국 특허청에서 열린 대학원생 발명대회
  - **동메달 수상 (상금 1만달러)**



- 관련 기술 현재 캘리포니아에 **startup** 차려 짐 **(**석태준 박사님**,** 권경목 박사님**, Ming Wu** 교수님**)**

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Equity Residential apartment buildings sale may bring Acheson development

UC Berkeley team wins $10,000 for cloud-storage innovation

Silicon photonic switch 미국 특허

(12) United States Patent
Seok et al.

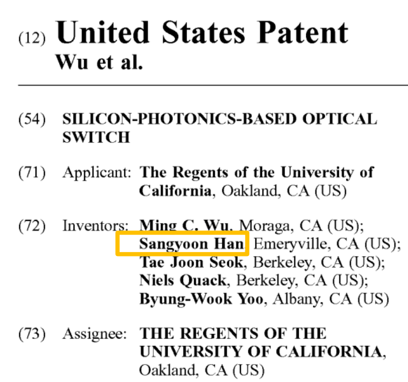
(54) SILICON-PHOTONICS-BASED OPTICAL SWITCH WITH LOW POLARIZATION SENSITIVITY

(71) Applicant: The Regents of the University of California, Oakland, CA (US)

(72) Inventors: Tae Joon Seok, Berkeley, CA (US); Sangyoon Han, Emeryville, CA (US); Ming Chiang A Wu, Moraga, CA

(73) Assignee: The Regents of the University of California, Oakland, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under U.S.C. 154(b) by 0 days.



(12) United States Patent
Wu et al.

(54) SILICON-PHOTONICS-BASED OPTICAL SWITCH

(71) Applicant: The Regents of the University of California, Oakland, CA (US)

(72) Inventors: Ming C. Wu, Moraga, CA (US); Sangyoon Han, Emeryville, CA (US); Tae Joon Seok, Berkeley, CA (US); Niels Quack, Berkeley, CA (US); Byung-Wook Yoo, Albany, CA (US)

(73) Assignee: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA, Oakland, CA (US)

DGIST에 잘 오셨습니다!

- 4차 산업혁명 시대! 평생 직업은 업따!
- 공돌(순)이에게 최적화된 세상!

SCV의 삶

코인 채굴중...

공돌이가 바라본 SCV (온라인 발췌)

- **우리는 ~~돈되는건~~ 인류의 삶을 증진시키는 건 다한다!**

K-공돌이 진출 진로 (미국의 경우)

- **미국 top 20 정도의 공대 대학원 (박사, 포닥)에서 IT (전자공학, 컴퓨터공학)을 전공하면 구글, 애플, 퀄컴, 페이스북 등은 원하면 갈수 있다!**
- **연봉, 영주권, 의료보험, 집값….**

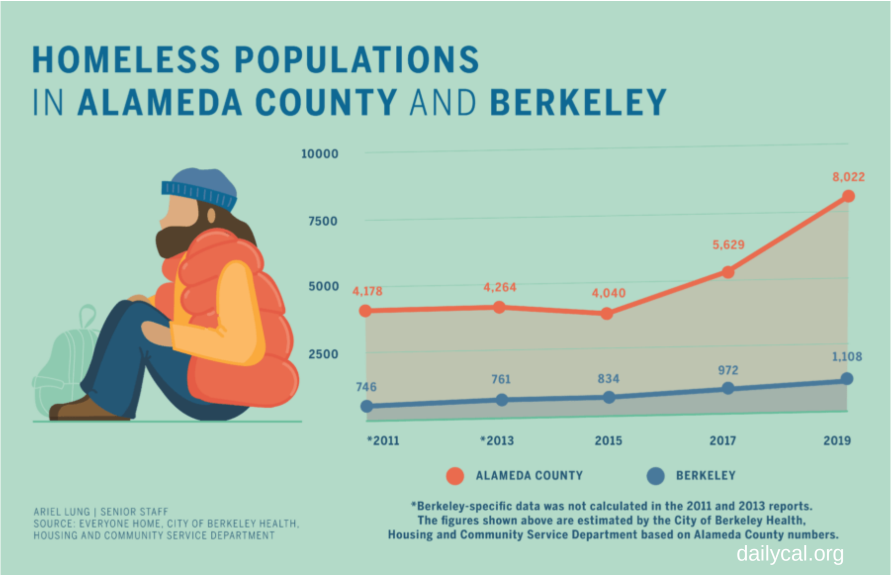
https://www.pinterest.co.kr/pin/263319909448423543/

- 이곳에서 박사가 굶고 사는 일은 업따

캘리포니아의 집값 문제

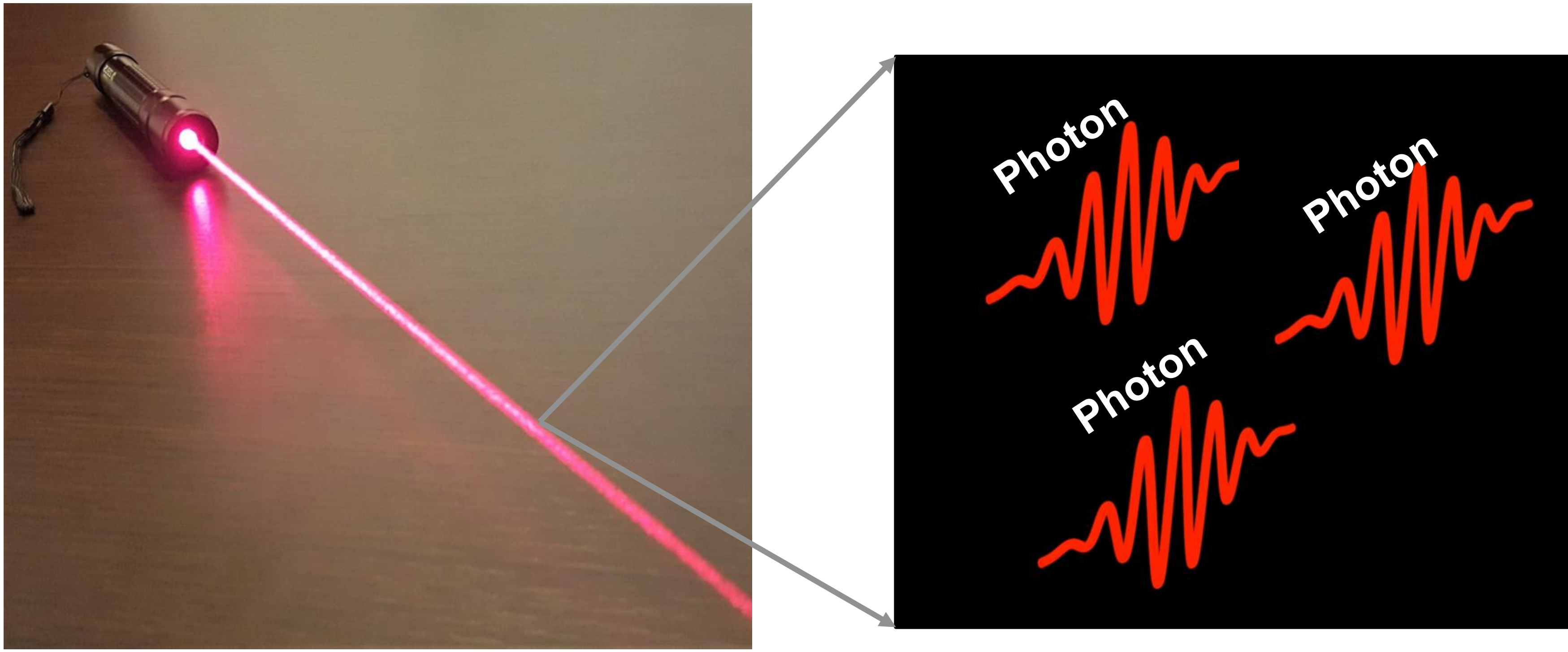
고속도로 아래의 노숙자 텐트들

실리콘밸리 주변 도시들 노숙자 증가율



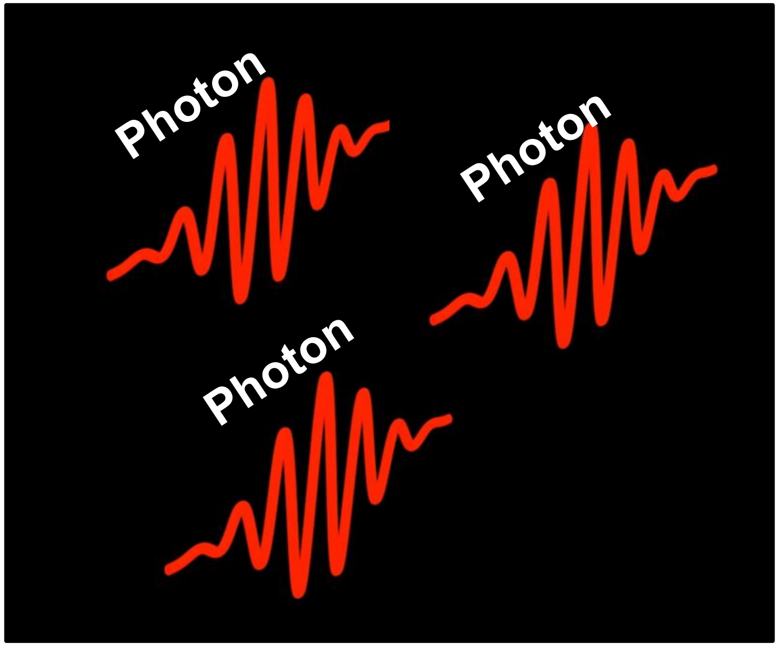
- 날씨라도 좋은 동네라서 다ㅎ......

빛도 양자 역학적인 시스템이다 (당근이지)



- 빛의 세기를 줄이고 줄이면 광자 (photon)이 된다
  - 광자: 더 이상 쪼갤 수 없는 빛의 기본 알갱이
- 마치 물질을 쪼개고 쪼개면 원자 (전자)가 되듯이

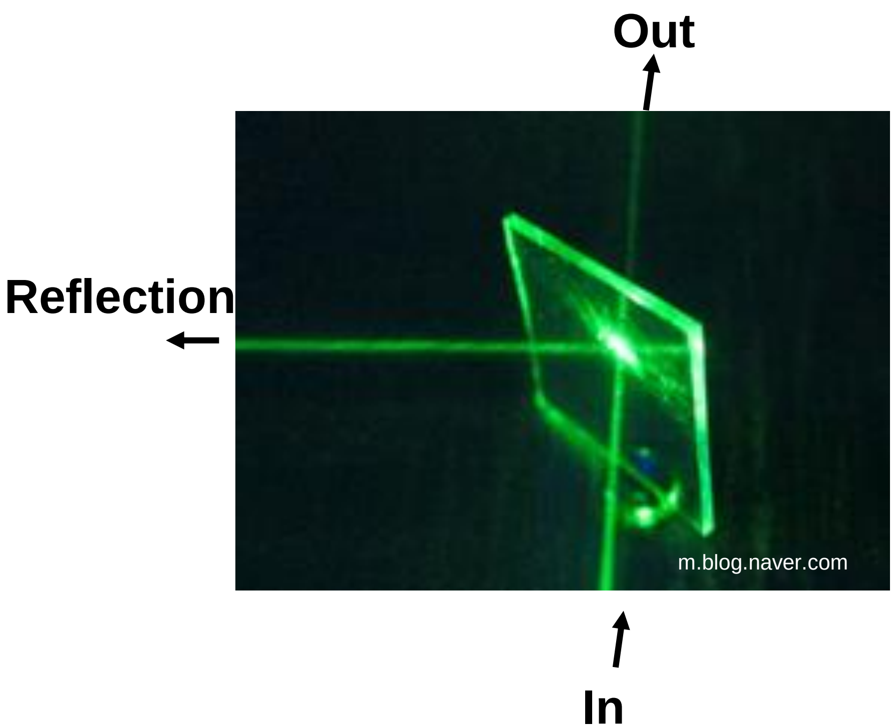
Photon as a qubit



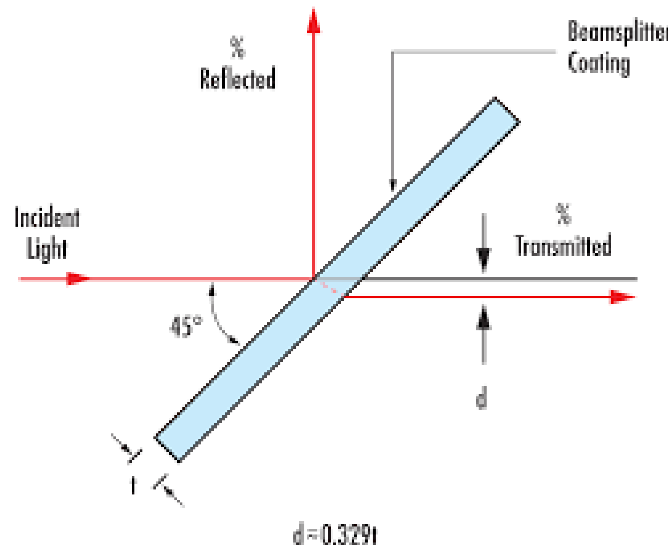
- 광자도 qubit 으로 사용 가능하다
- 여러가지 성질을 사용 가능: 위치, 편광, 모드 등등

Photon as a qubit

50:50 beam splitter

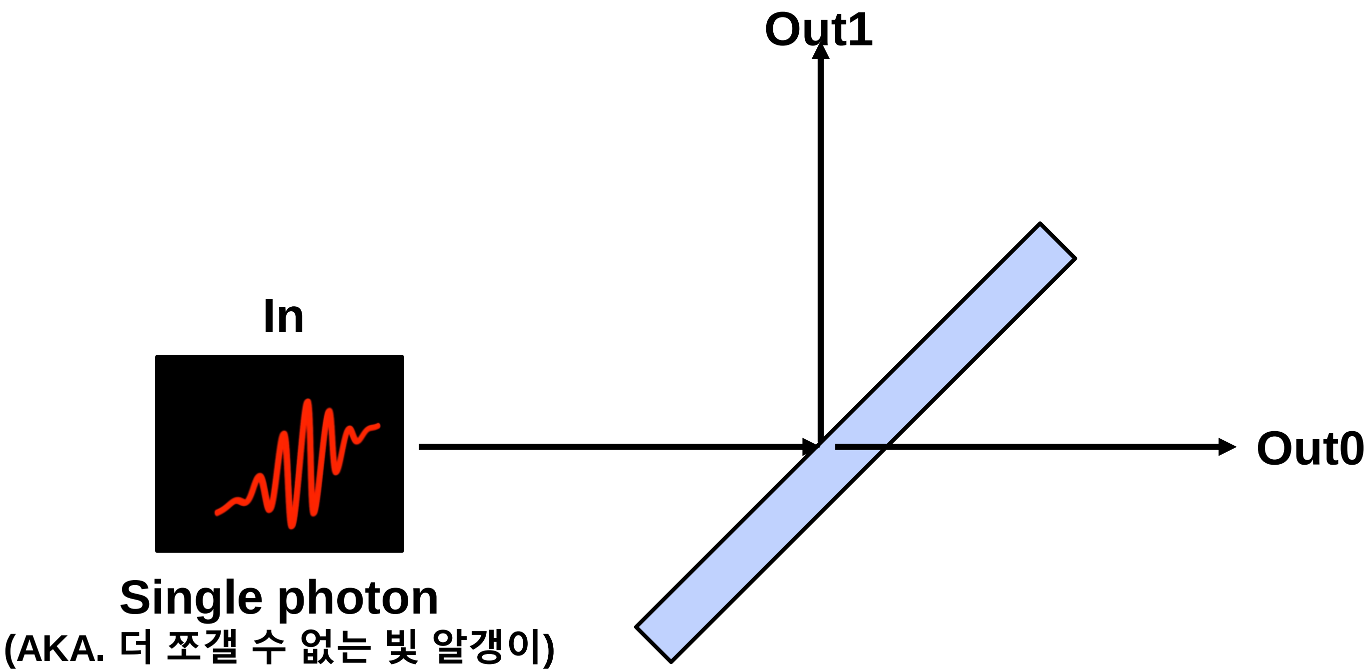


50:50 beam splitter



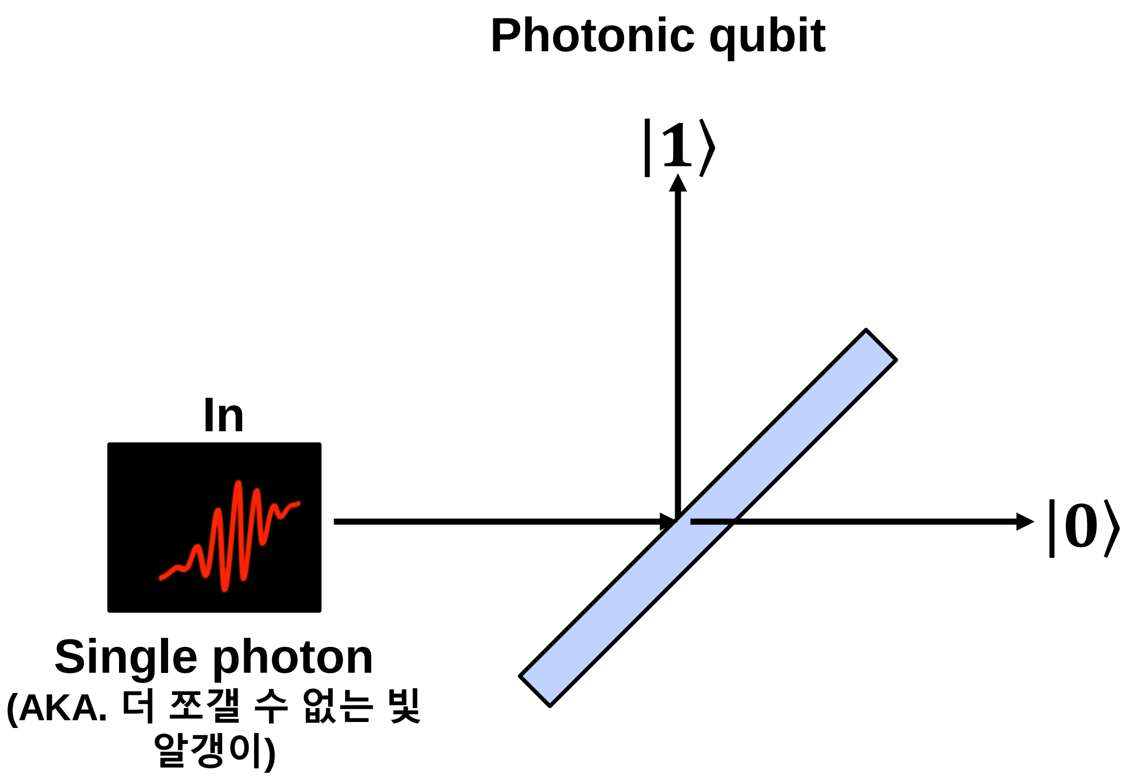
- **50:50으로 빛을 나눠주는 유리 (예: 슬라이드 글라스)**
- **만일 In 에 하나의 광자가 들어간다면?**

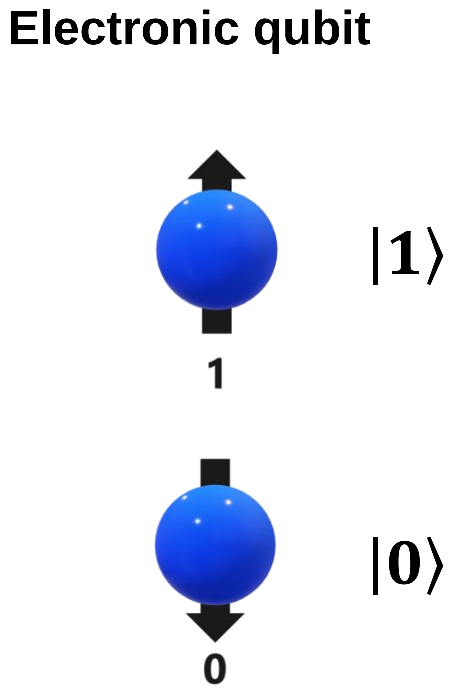
Single photon transmitting through beam splitter



- Pop quiz: photon은 어디로 갈까요?
  - 1) out0
  - 2) out1
  - 3) 알수 없다

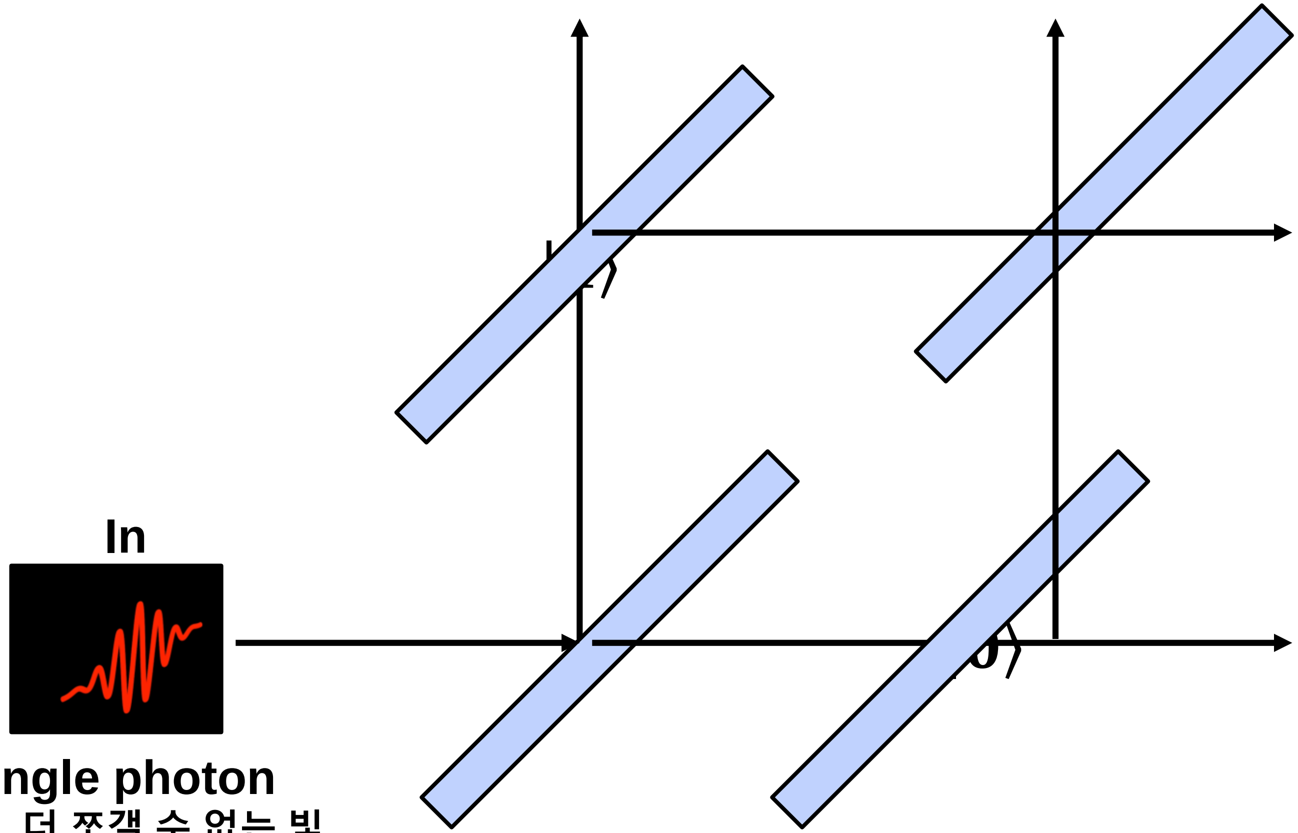
Single photon transmitting through beam splitter





How to make a photonic quantum computer?

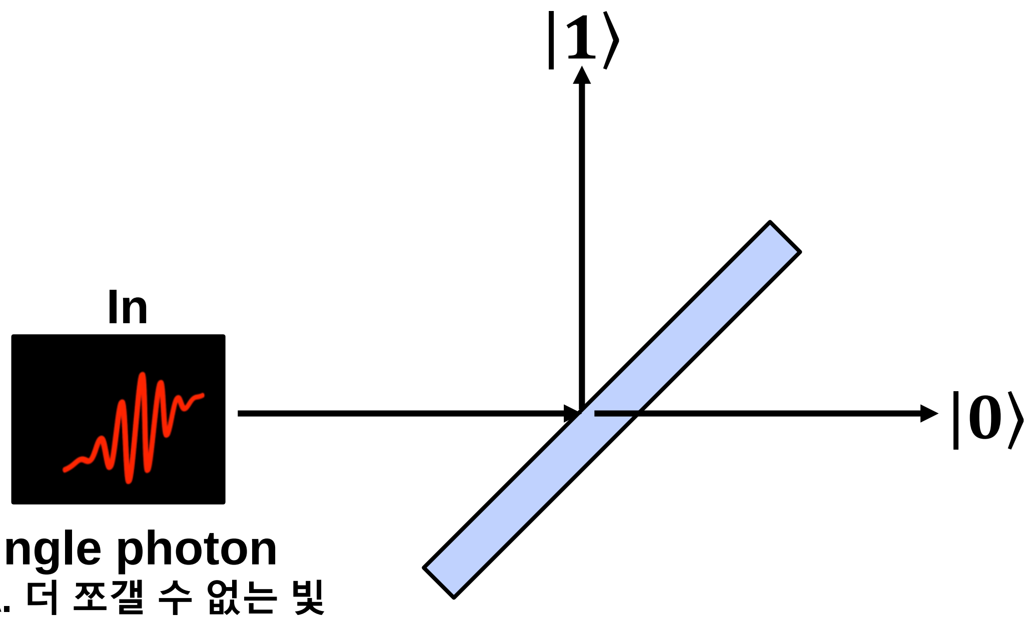
In



Single photon
(AKA. 더 쪼갤 수 없는 빛 알갱이)

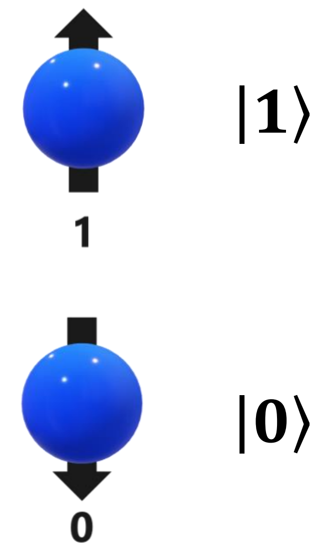
Single photon transmitting through beam splitter

Photonic qubit

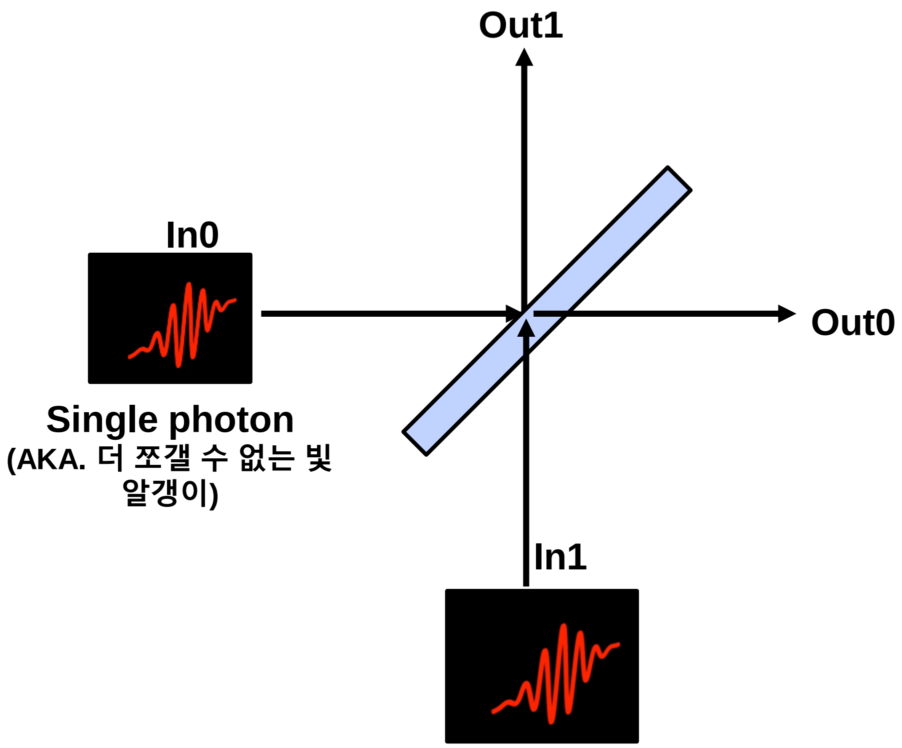


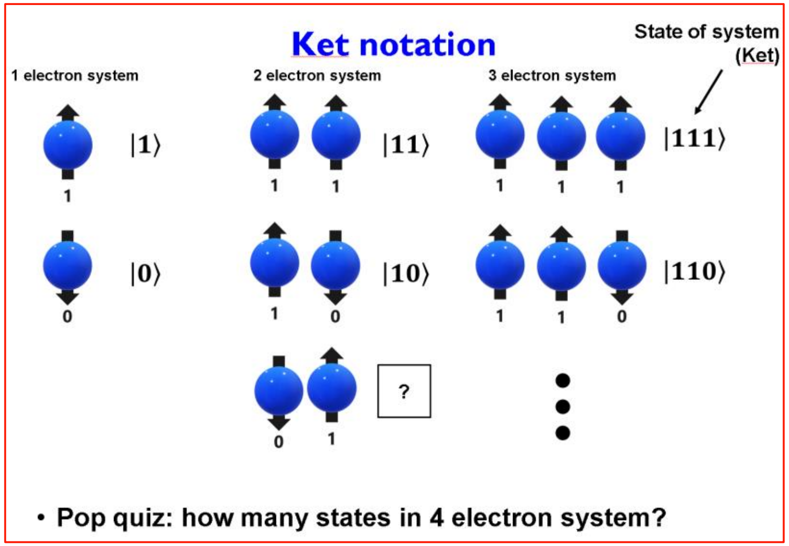
Single photon
(AKA. 더 쪼갤 수 없는 빛 알갱이)

Electronic qubit



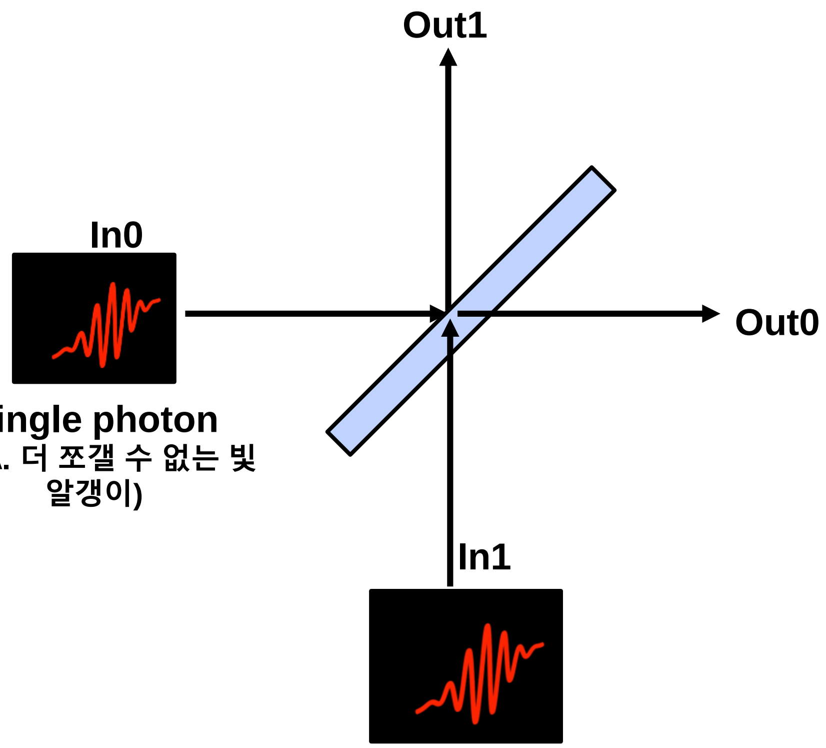
Two photon system





Pop quiz: How do you express the state of the system in Ket notation?

Two photon system



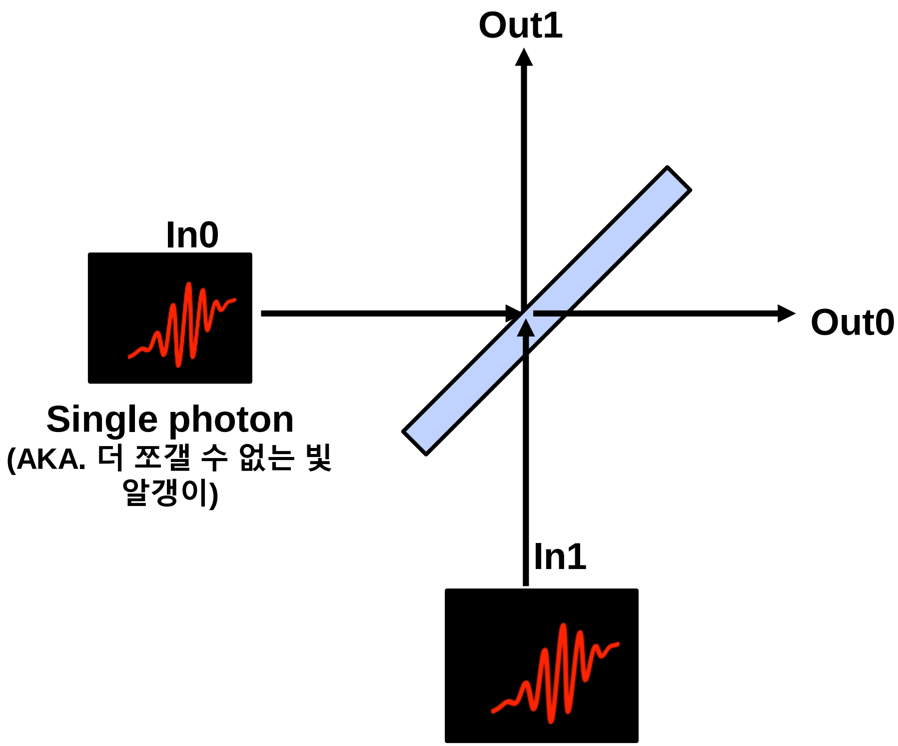
Single photon
(AKA. 더 쪼갤 수 없는 빛 알갱이)

이렇게 나타내면 됩니다!

$$|?\quad ?\rangle$$

Pop quiz: How do you express the state of the system in Ket notation?

Two photon system



Out0 Out1

$$|1\,1\rangle$$

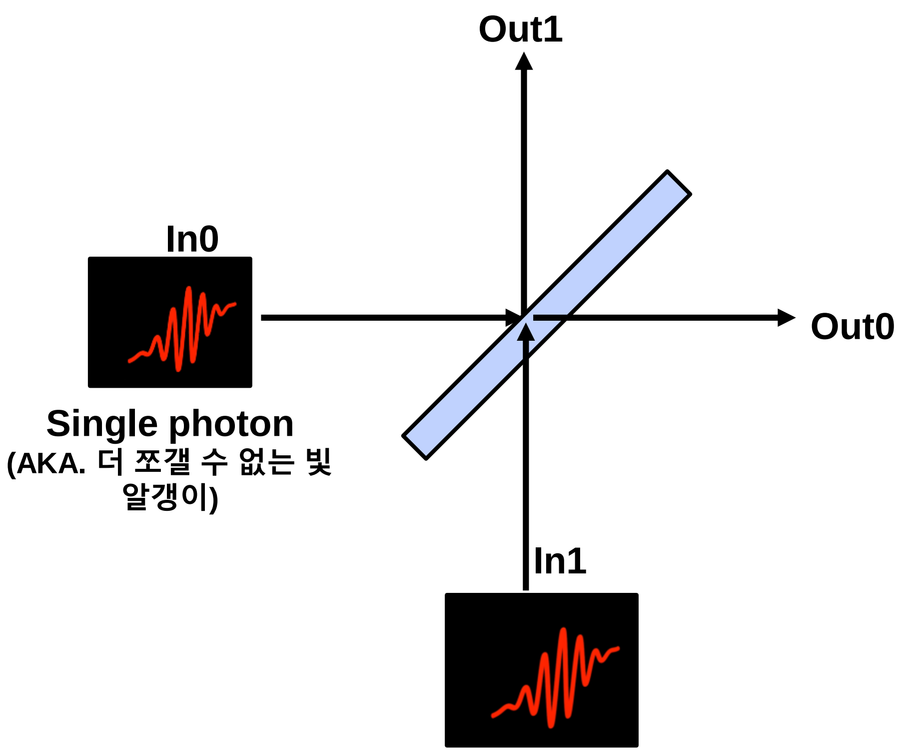
$$|2\,0\rangle$$

$$|0\,2\rangle$$

$$|1\,1\rangle$$

Pop quiz: How do you express the state of the system in Ket notation?

Two photon system



Out0 Out1

$|1\,1\rangle$

$|2\,0\rangle$

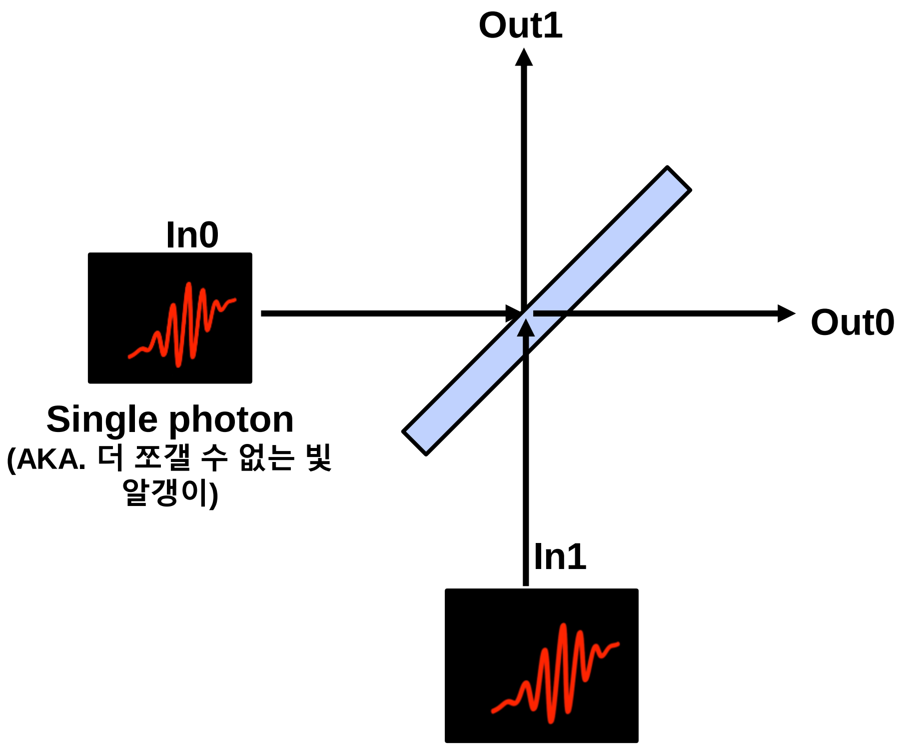
$|0\,2\rangle$

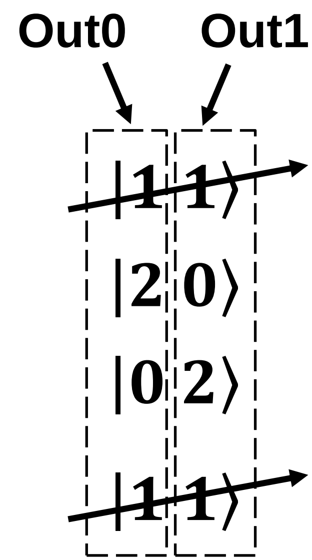
$|1\,1\rangle$

$$\Psi = \alpha_{11}|1\ 1\rangle + \alpha_{20}|2\ 0\rangle + \alpha_{02}|0\ 2\rangle$$

$|\alpha_{11}|^2,\ |\alpha_{20}|^2,\ |\alpha_{02}|^2$ 각각 얼마일까요?

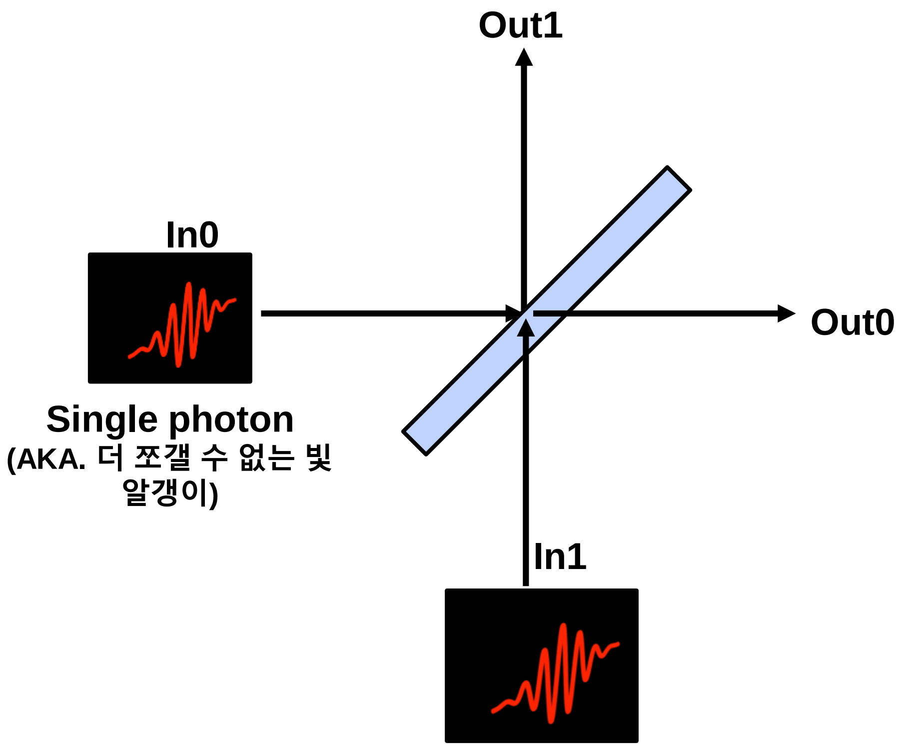
2개의 동일한 광자가 동시에 beam splitter에 도달할 경우





- 항상 같은 쪽으로만 간다 (Hong–Ou–Mandel effect)
  - 이건 그냥 받아들입시다…

2개의 동일한 광자가
동시에 beam splitter에 도달할 경우



Out0	Out1

$\cancel{|1\;1\rangle}$

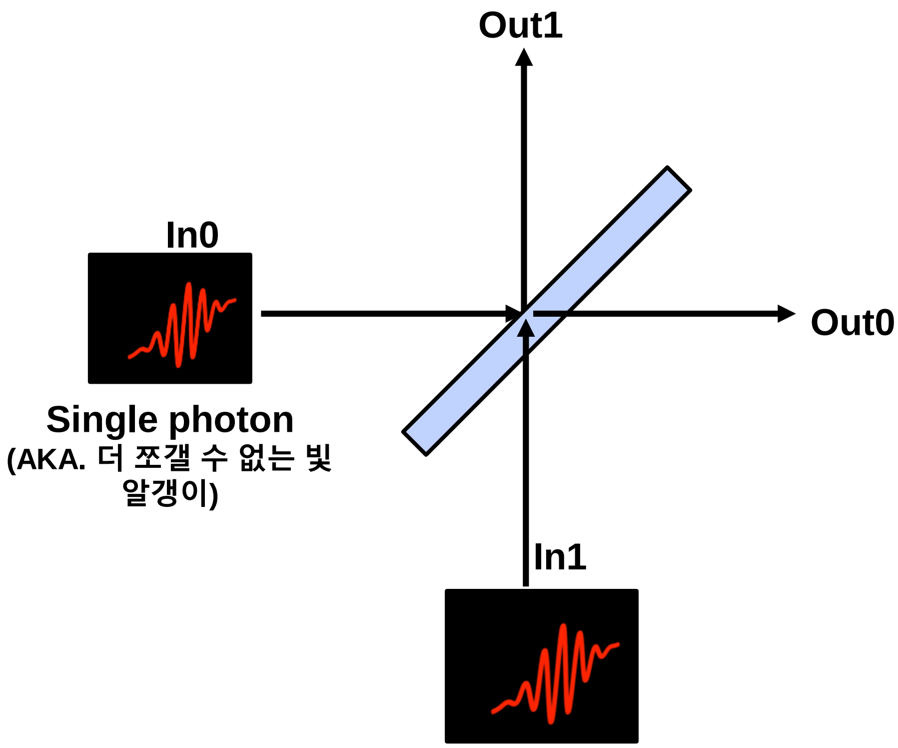
$|2\;0\rangle$

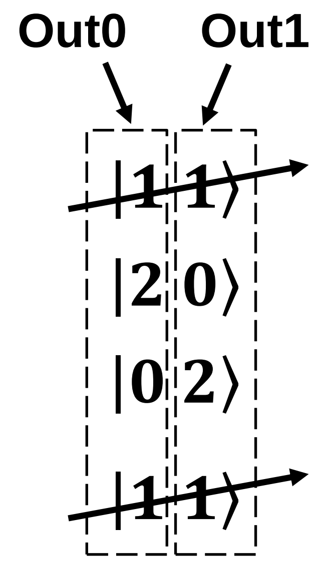
$|0\;2\rangle$

$\cancel{|1\;1\rangle}$

$$\Psi = \overset{?}{\alpha_{11}}|1\;1\rangle + \overset{0}{\cancel{\alpha_{20}}}|2\;0\rangle + \overset{0}{\cancel{\alpha_{02}}}|0\;2\rangle$$

약간의 시간차가 있을 경우



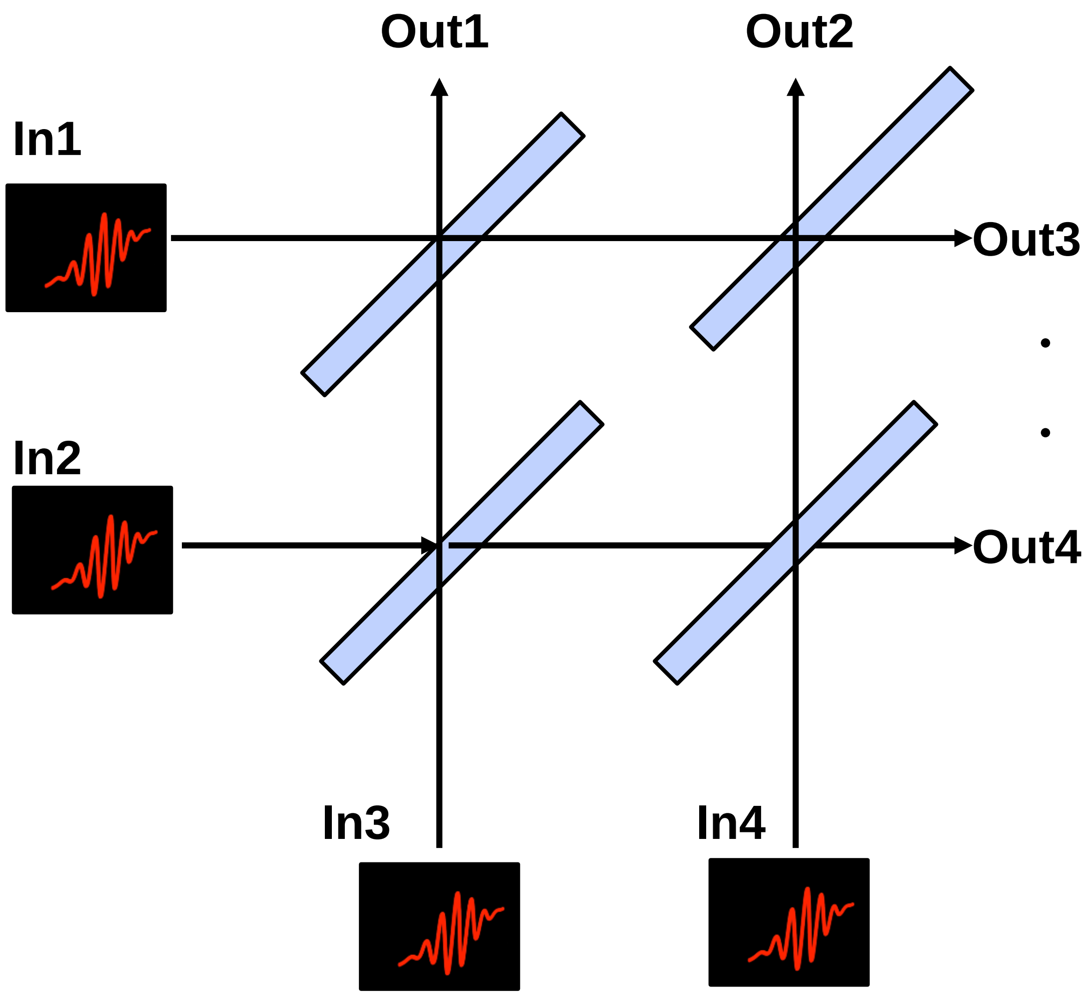


$$\Psi = \alpha_{11}|1\,1\rangle + \alpha_{20}|2\,0\rangle + \alpha_{02}|0\,2\rangle$$

시간차가 클수록 $|\alpha_{20}|^2,\ |\alpha_{02}|^2$ 는 커지고, $|\alpha_{11}|^2$ 는 작아 짐

Boson sampler (광학식 양자컴퓨터의 예)

$$\Psi = \alpha_{1111}|1\ 1\ 1\ 1\rangle + \alpha_{2110}|2\ 1\ 1\ 0\rangle + \alpha_{2210}|2\ 2\ 1\ 0\rangle + \ \ldots..$$



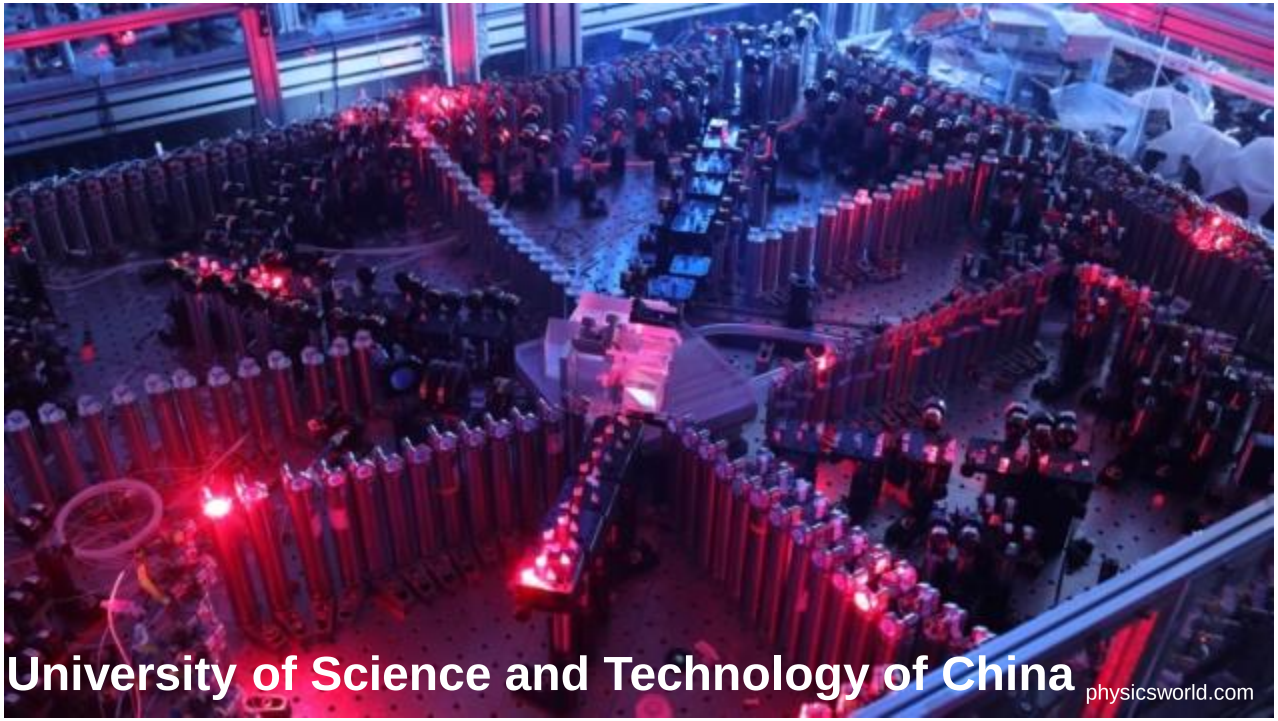
1. 모든 input에 광자가 동시에 들어가면?

2. 약간씩 시간차이를 두고 들어가면?

- Input과 output의 개수가 늘어나면 경우의 수는 기하급수적으로 늘어난다
- 슈퍼컴퓨터를 사용해도 α들(확률)을 계산하는 것이 매우 어렵다

Boson sampler (광학식 양자컴퓨터의 예)

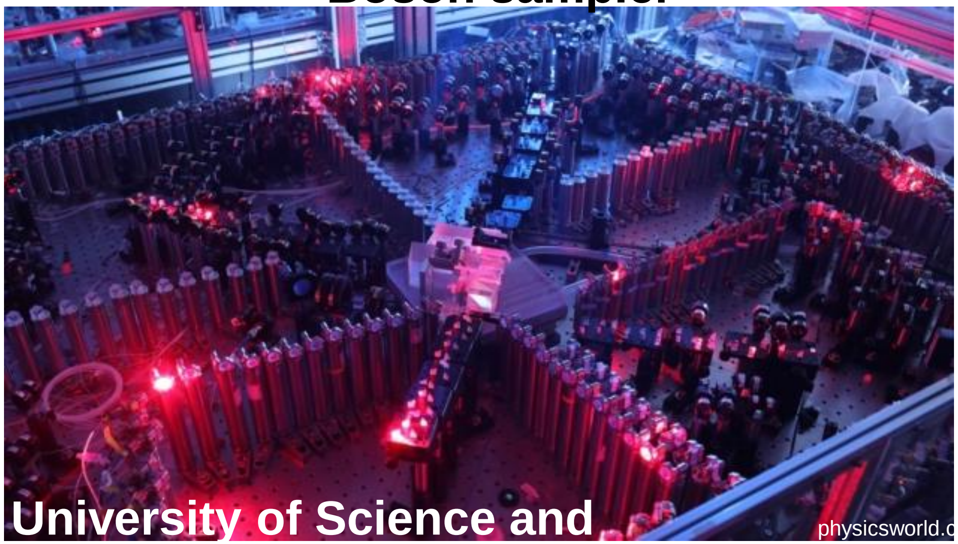
Boson sampler



- **Beam splitter 300개, 거울 75개**
- **100개 photon input, 100 개 photon output**

슈퍼컴퓨터와 비교

Boson sampler



Sunway TaihuLight (Super computer)

200초

25억년

RESEARCH Science 2020

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

Quantum computers promise to perform certain tasks that are believed to be intractable to classical computers. Boson sampling is such a task and is considered a strong candidate to demonstrate the quantum computational advantage. We performed Gaussian boson sampling by sending 50 indistinguishable single-mode squeezed states into a 100-mode ultralow-loss interferometer with full connectivity and random matrix—the whole optical setup is phase-locked—and sampling the output using 100 high-efficiency single-photon detectors. The obtained samples were validated against plausible hypotheses exploiting thermal states, distinguishable photons, and uniform distribution. The photonic quantum computer, *Jiuzhang*, generates up to 76 output photon clicks, which yields an output state-space dimension of 10^{30} and a sampling rate that is faster than using the state-of-the-art simulation strategy and supercomputers by a factor of ~10^{14}.

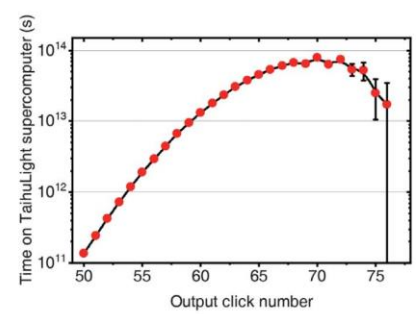
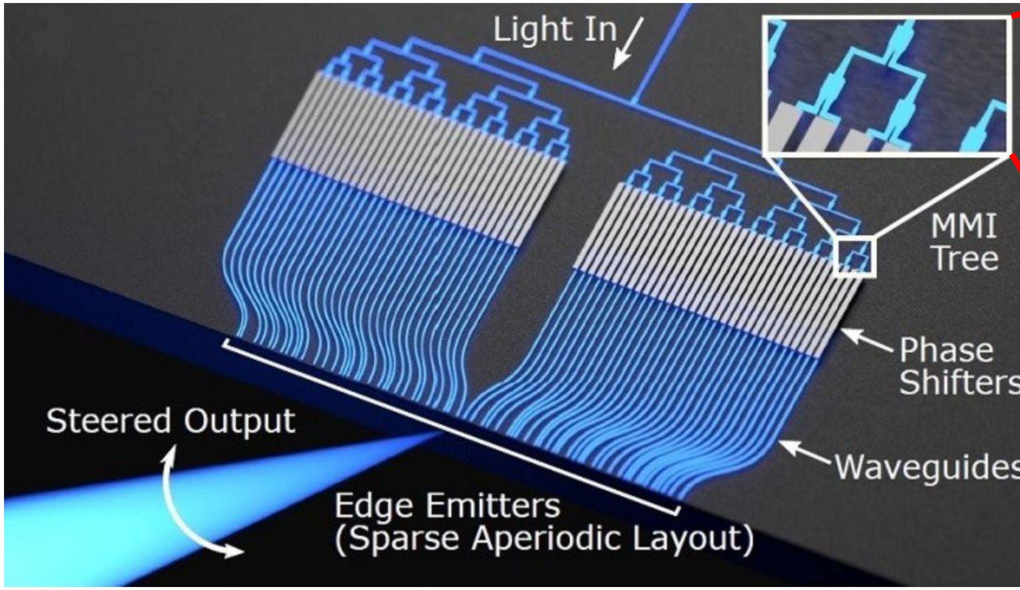
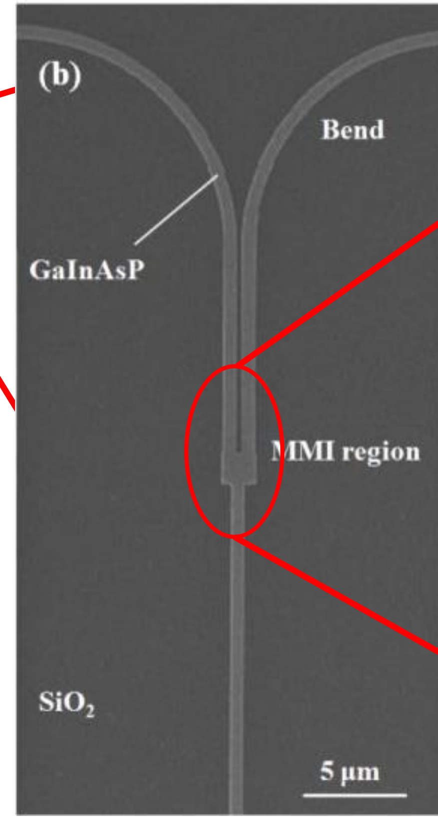


Fig. 4. Classical computational cost. The estimated time cost on a Sunway TaihuLight supercomputer is plotted as a function of the output photon click number. The error bar is calculated from Poissonian counting statistics of the raw detected events.

Waveguide splitter

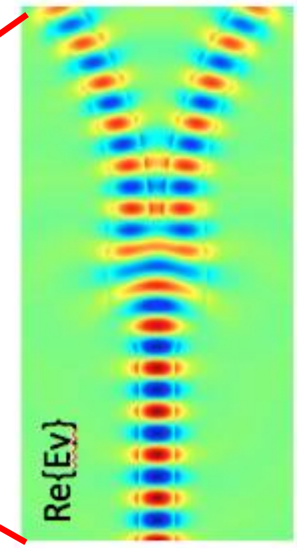


SEM image



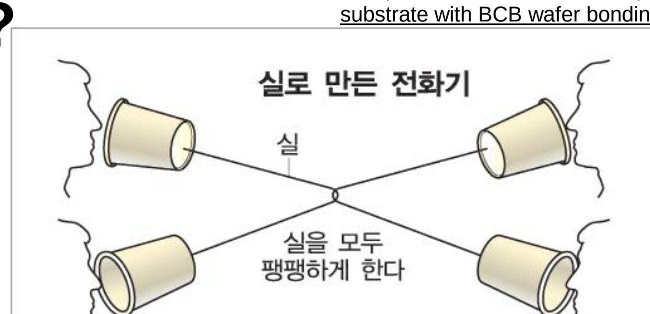
Compact InP-based 1×2 MMI splitter on Si substrate with BCB wafer bonding for membrane

Light propagation



optoelectronics.eecs.berkeley.edu

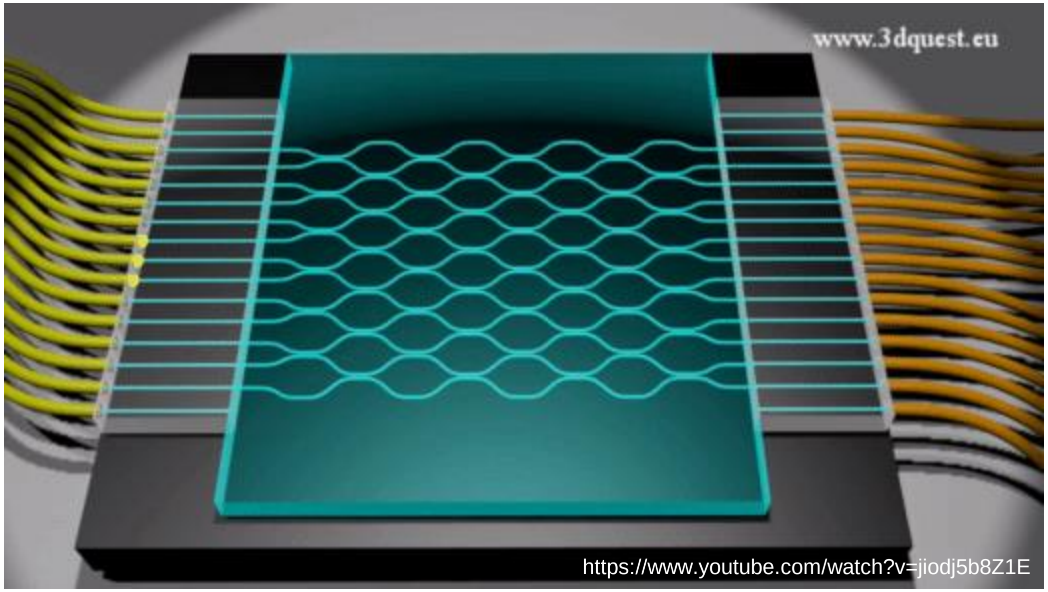
- **Very intuitive looking?**



https://www.seoul.co.kr/news/newsView.php?id=20060818022003

Boson sampler, 빛으로 하는 야바위...

Chip scale Boson sampler



- 내 광자는 어디로 갔을까??
- 내 떡은 어디로 갔을까??

잠시만... 그런데 내가 이 짓을 왜 하고 있지??

- 돈ㅈㄹ 야바위 ....
- 재능낭비 야바위....

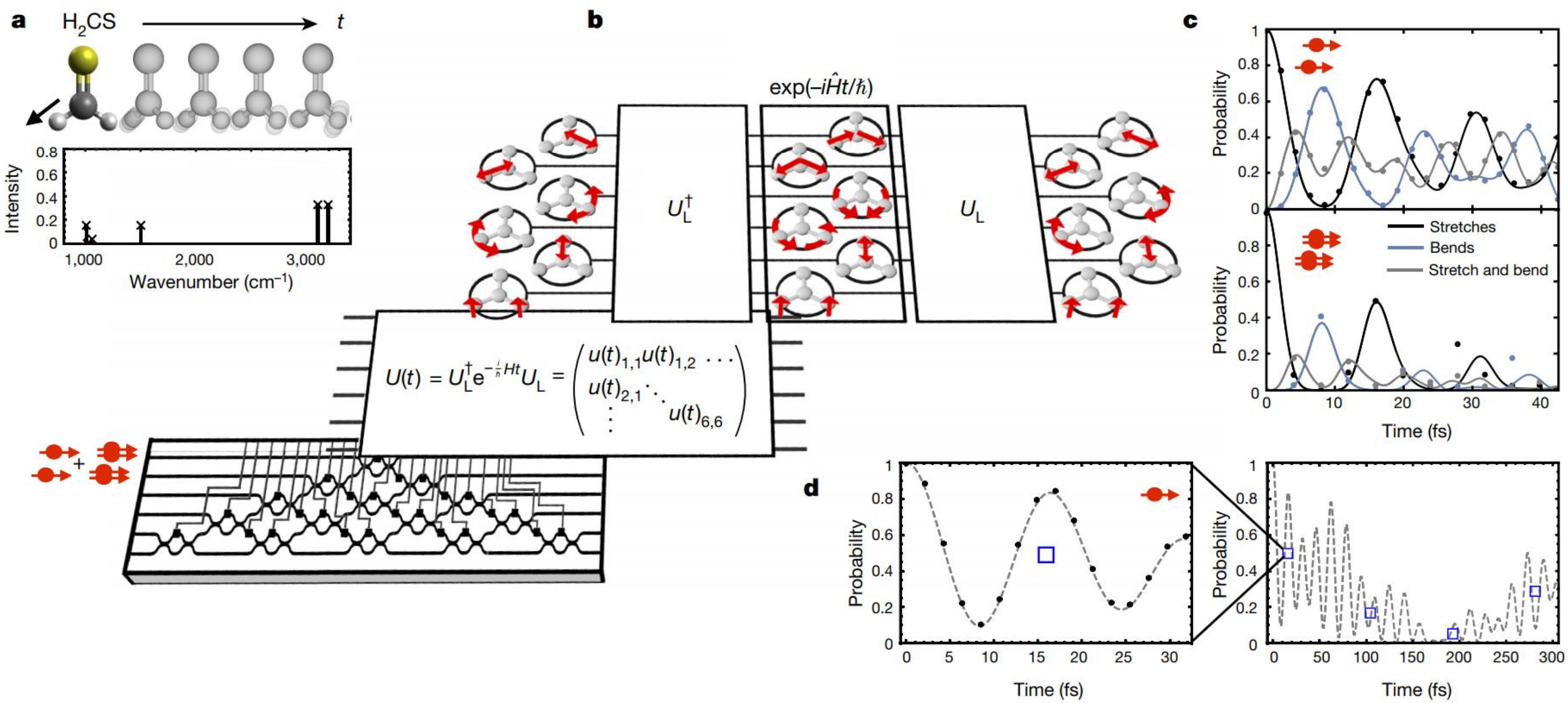
Nature 2018

ARTICLE

https://doi.org/10.1038/s41586-018-0152-9

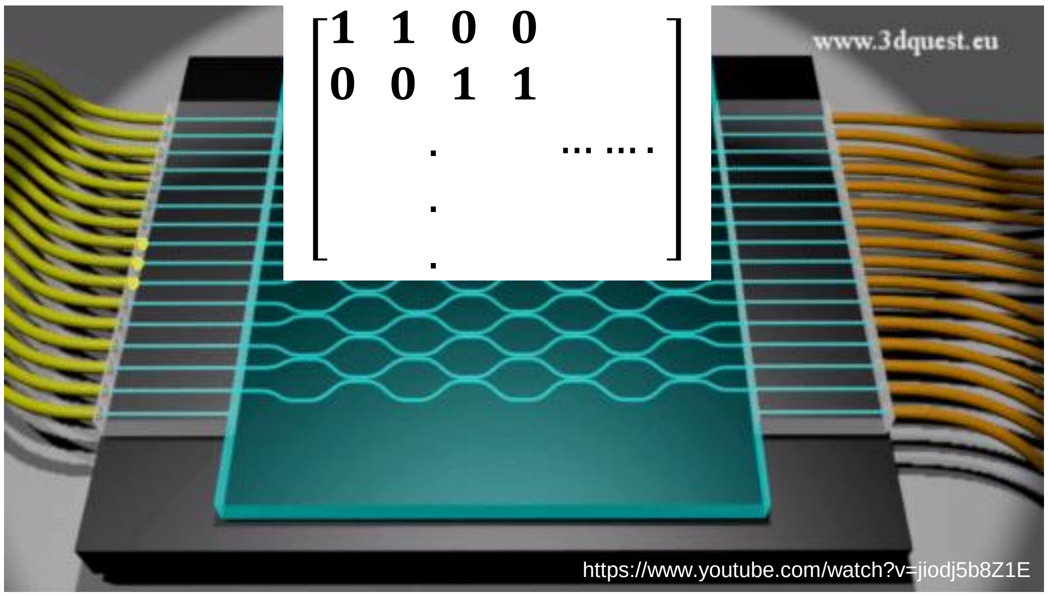
Simulating the vibrational quantum dynamics of molecules using photonics

Chris Sparrow[1,2], Enrique Martín-López[3], Nicola Maraviglia[1], Alex Neville[1], Christopher Harrold[1], Jacques Carolan[4], Yogesh N. Joglekar[5], Toshikazu Hashimoto[6], Nobuyuki Matsuda[7], Jeremy L. O'Brien[1], David P. Tew[8] & Anthony Laing[1]*

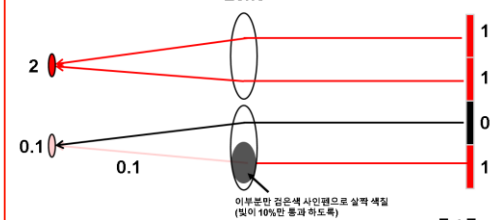


광자를 가지고 하는 행렬 곱셈

$$\begin{bmatrix}1\\1\\0\\1\\0\\1\\1\\1\\1\end{bmatrix} \quad \begin{bmatrix}1 & 1 & 0 & 0 & & \\ 0 & 0 & 1 & 1 & & \\ & & \cdot & & \cdots \; \cdots\cdot & \\ & & \cdot & & & \\ & & \cdot & & & \end{bmatrix} \quad \begin{bmatrix}2\\3\\0\\1\\0\\0\\0\\1\\1\end{bmatrix}$$



그럼 이건?

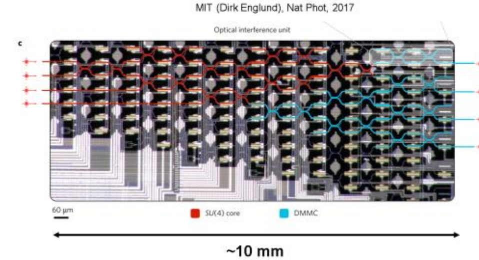


$$\begin{bmatrix}2\\0.1\end{bmatrix} = \begin{bmatrix}1 & 1 & 0 & 0\\ 0 & 0 & 1 & 0.1\end{bmatrix} \times \begin{bmatrix}1\\1\\0\\1\end{bmatrix}$$

2차 벡터 2x4 행렬 4차 벡터

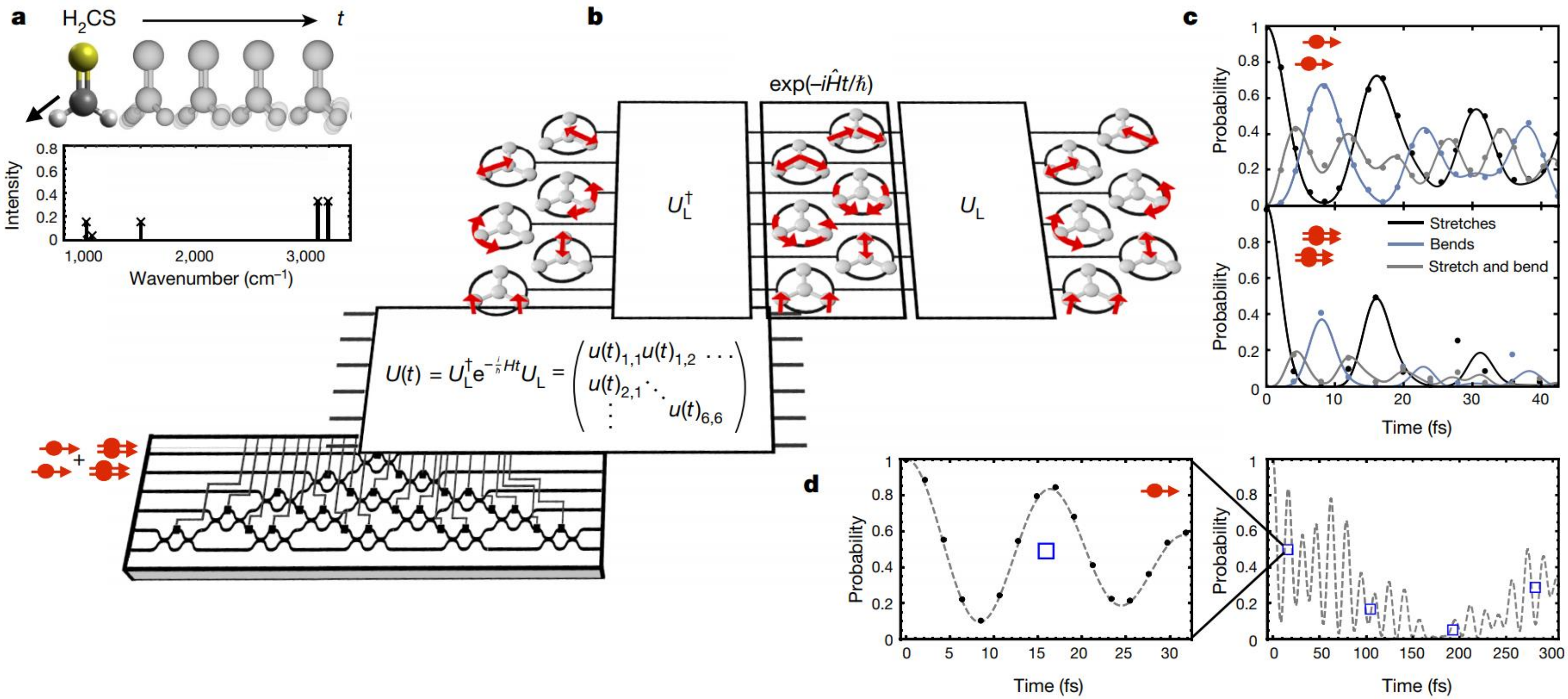
Optical neural net on a chip

MIT (Dirk Englund), Nat Phot, 2017



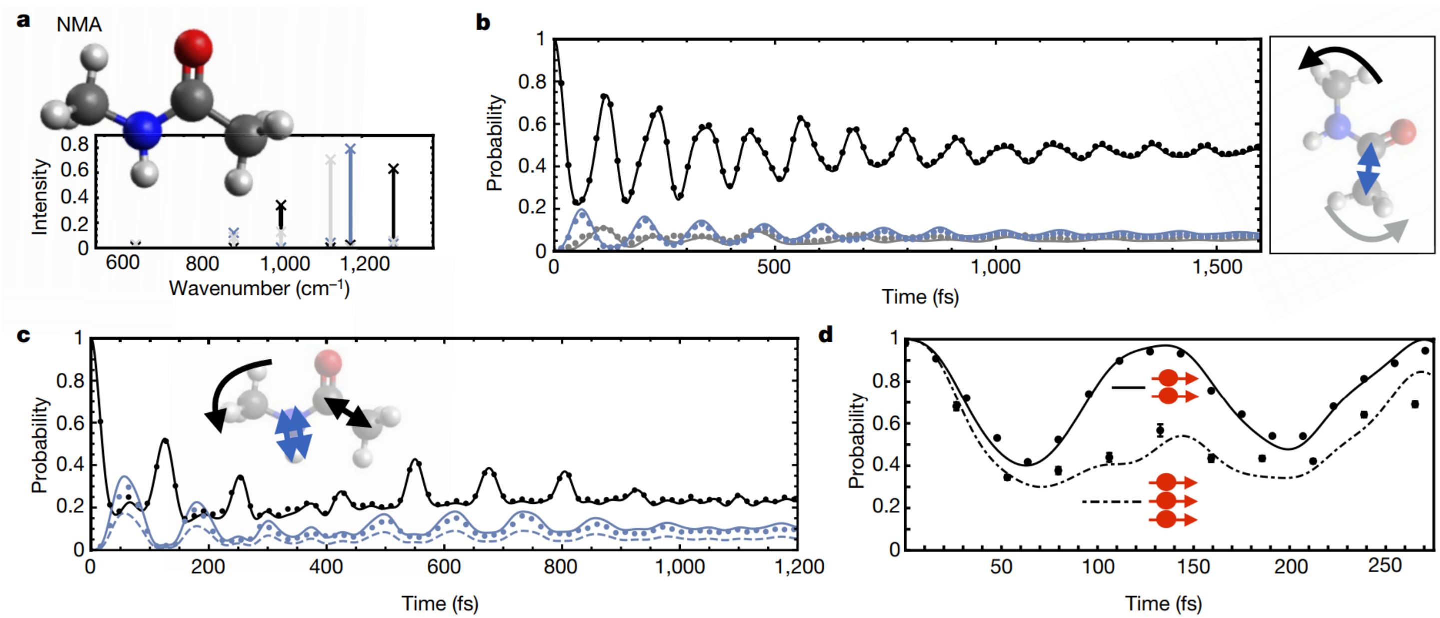
- Building optical neural network using waveguides
  - i.e. Photonic Integrated Circuits (PIC)

분자의 거동을 시뮬레이션



- 분자들을 지배하는 방정식 → 행렬
- 원자들을 광자에 대응
- 단분자 화학반응 시뮬레이션 (새로운 물질 합성, 거대 분자 구조 탐색 등등)

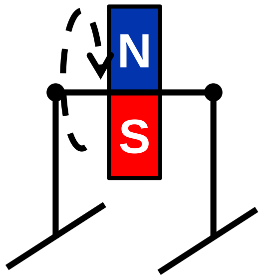
분자의 거동을 시뮬레이션



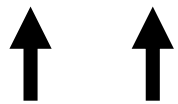
- 분자들을 지배하는 방정식 → 행렬
- 원자들을 광자에 대응
- 단분자 화학반응 시뮬레이션 (새로운 물질 합성, 거대 분자 구조 탐색 등등)

자석 방향 문제 (Ising problem)

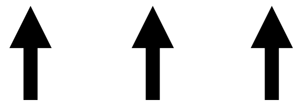
Free to rotate



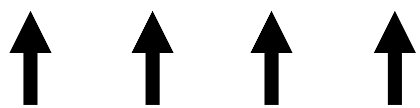
2 magnets



3 magnets



4 magnets



- **It is a NP-hard problem**
- **N magnets → 2^N combination to compute**

Sangyoon Han, PhD

- **Seoul National University, 2006-2010**
  - **B.S. in Electrical Engineering, Summa Cum Laude**
  - **GPA: 4.19/4.30 (major), 4.08/4.30 (overall)**
- **UC Berkeley, 2010-2016 (rank #2 in EE in US)**
  - **M.S./Ph.D. in Elec. Eng. & Comp. Sci.**
  - 한국고등교육재단 해외유학 장학생
- **KAIST, 2016-2020**
  - **Postdoc in physics**
  - 전문연구요원 **(병역)**
- **Train Yoga every morning**

lawlite.tistory.com

junilearning.com

Sangyoon Han doing Scorpion

hancinema.net

Undergraduate School

- 서울대학교 최우수 이공계 꿈나무 장학생, 2006
  - 서울대 공과대학 1학년 전체 학생 중 학점 최우수자 16명 선발
- 대학생 공학수학경시대회 우수상, 2007
  - By 대한수학회
- 중국 칭화대학교 교환 장학생, 2008
  - 서울대학교 공과대학 선발
- 한국고등교육재단 해외유학장학생 선발 후 미국 대학원 진학
  - 5년간 등록금 및 생활비 지원

칭화대 앞

한국고등교육재단 사옥

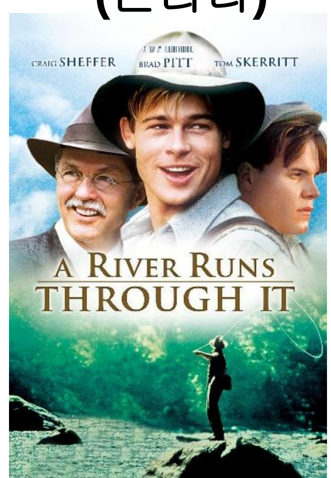
Before college

- 전주 화교 소학교 (pre-초등학교 & 초등학교 저학년), 1992년~1995년
  – 한국 사람 입니다.
  ~~– 한국말~~ 중국말 잘합니다.
- 중국 하얼빈 거주 (초등학교), 1998년~1999년
- 미국 Montana 거주 (고등학교), 2002년~2003년
  – 미국 고등학교 교환학생

하얼빈 얼음축제

bbc.com

흐르는 강물처럼
(몬타나)

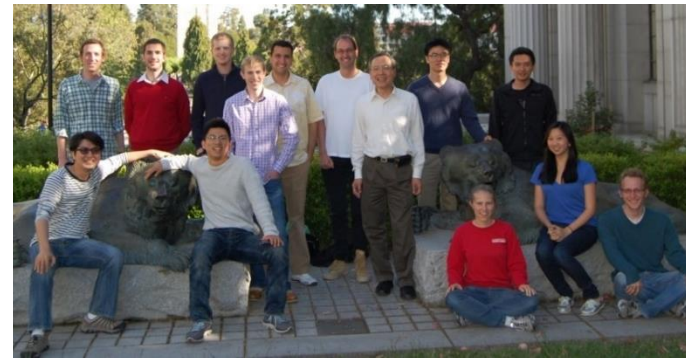


fandangonow.com

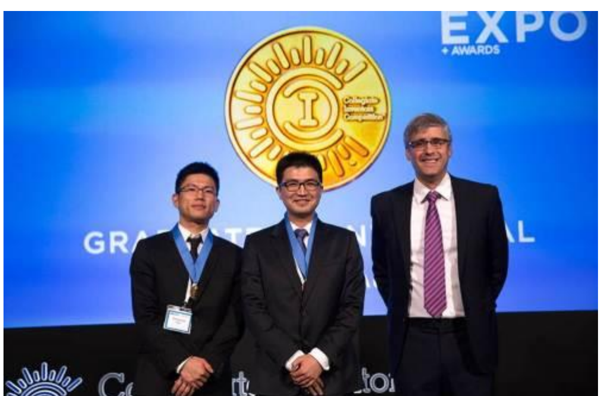
전주 화교 소학교

Graduate School

- **Corning Outstanding Student Paper Competition, 2014**
  - 미국 코닝사 후원 학생 논문 경진 대회
  - **Finalist (341개 논문 중 상위 6개 선발)**
- **Collegiate Inventors Competition, 2015**
  - 미국 특허청에서 열린 대학원생 발명대회
  - **동메달 수상 (상금 1만달러)**



- 관련 기술 현재 캘리포니아에 **startup** 차려 짐 **(**석태준 박사님**,** 권경목 박사님**, Ming Wu** 교수님**)**

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UC Berkeley team wins $10,000 for cloud-storage innovation

Silicon photonic switch 미국 특허

(12) United States Patent
Seok et al.

(54) SILICON-PHOTONICS-BASED OPTICAL SWITCH WITH LOW POLARIZATION SENSITIVITY

(71) Applicant: The Regents of the University of California, Oakland, CA (US)

(72) Inventors: Tae Joon Seok, Berkeley, CA (US; Sangyoon Han, Emeryville, CA (; Ming Chiang A Wu, Moraga, CA

(73) Assignee: The Regents of the University of California, Oakland, CA (US)

(*) Notice: Subject to any disclaimer, the term patent is extended or adjusted un U.S.C. 154(b) by 0 days.

(12) United States Patent
Wu et al.

(54) SILICON-PHOTONICS-BASED OPTICAL SWITCH

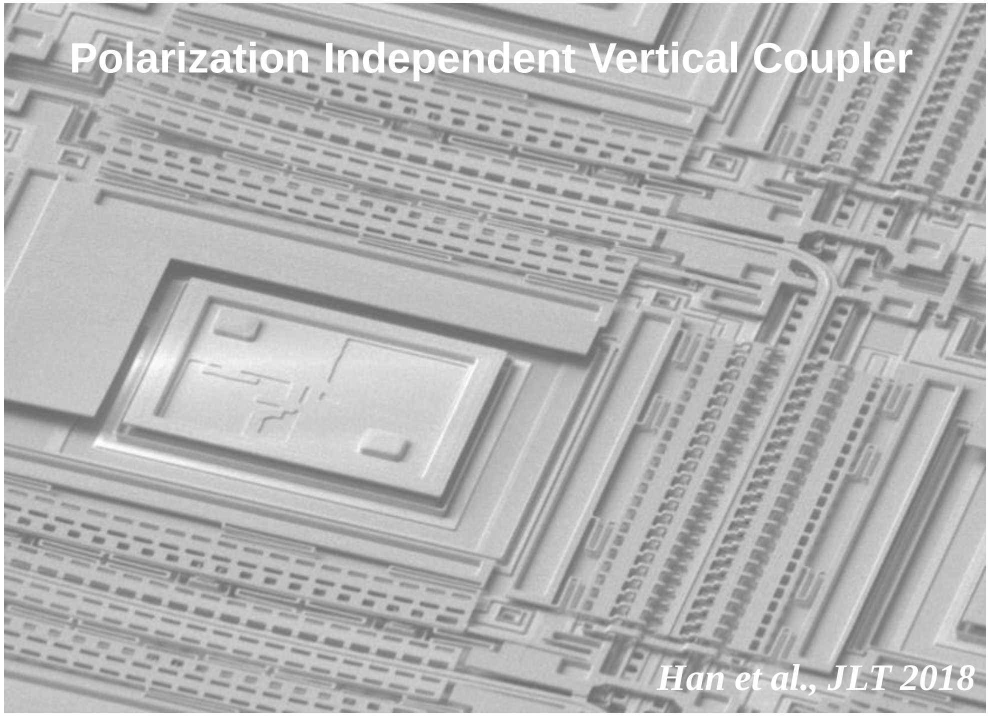
(71) Applicant: The Regents of the University of California, Oakland, CA (US)

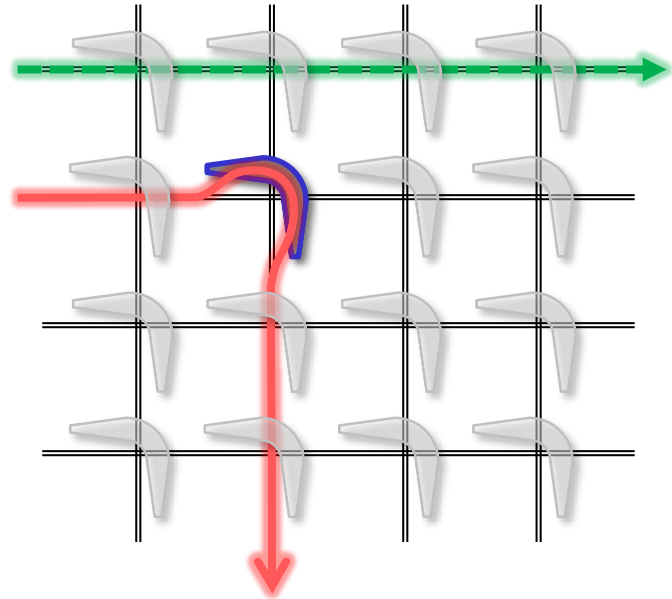
(72) Inventors: Ming C. Wu, Moraga, CA (US); Sangyoon Han, Emeryville, CA (US); Tae Joon Seok, Berkeley, CA (US); Niels Quack, Berkeley, CA (US); Byung-Wook Yoo, Albany, CA (US)

(73) Assignee: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA, Oakland, CA (US)

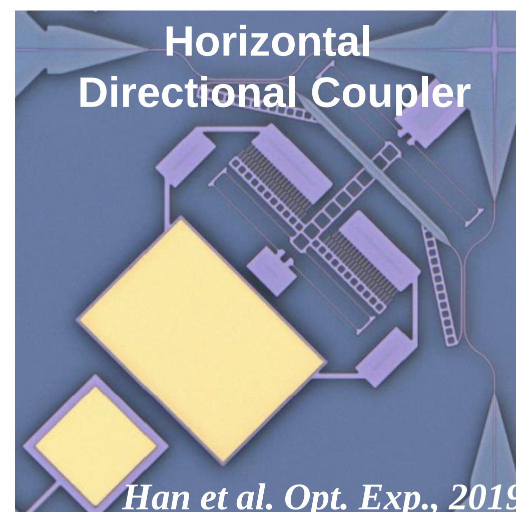
Silicon photonic switch for data centers

Generation IV

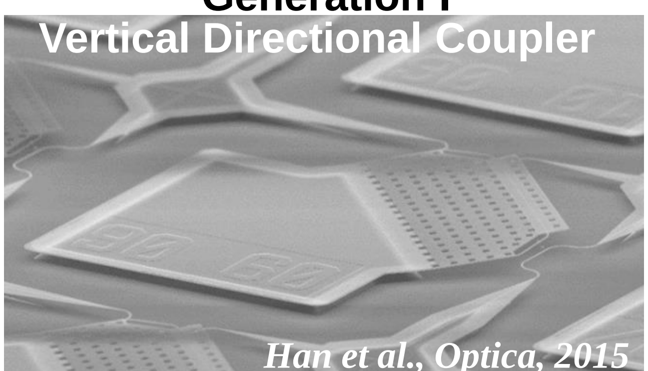




Generation III



Generation I



Generation II

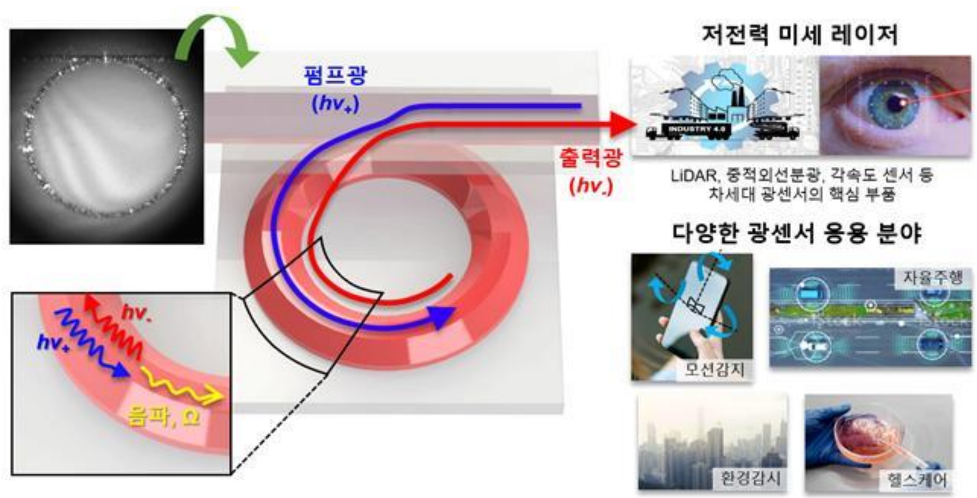
Postdoc

https://doi.org/10.1038/s41467-020-19799-2 OPEN

Universal light-guiding geometry for on-chip resonators having extremely high Q-factor

Dae-Gon Kim [1,2,6], Sangyoon Han [1,3,6], Joonhyuk Hwang [1], In Hwan Do [2], Dongin Jeong [2], Ji-Hun Lim [4], Yong-Hoon Lee [4], Muhan Choi [4], Yong-Hee Lee [1], Duk-Yong Choi [5✉] & Hansuek Lee [1,2✉]

"국내 연구진 "기존 성능 100배 이상의 브릴루앙 레이저 구현 성공"
[매일경제] [뉴스1] [전자신문] [인공지능신문] [메디컬투데이] [뉴스프리존] [뉴스핌] [헬로티]

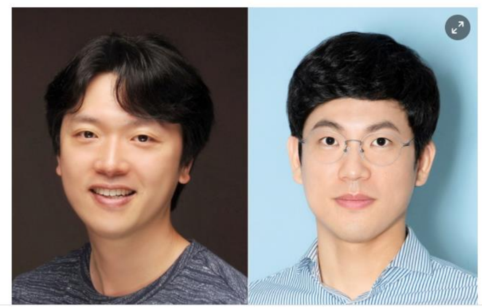


홈 > FOCUS > 기술

KAIST 이한석·이용희 교수 연구팀, 초소형·저전력·저잡음 브릴루앙 레이저 구현 성공

최광민 기자 | 입력 2020.12.23 21:22 | 댓글 0

낮은 펌프 에너지로 동작하는 브릴루앙 레이저를 반도체 칩 상에 구현, 자율주행용 거리·회전 감지 센서 등 초정밀 센서의 측정 정확도를 개선



- 빛을 칼코겐 화합물 반도체 칩에 오래 가두는 기술 개발
- 기존 기술에 비해 **10**배 향상
- 음파 레이저 **(**브릴루앙 레이저**)** 구현 가능

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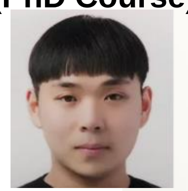

- **Started on Feb/2020**
- **2 PhD, 2 MS, 1 BS/MS students**
- **1**년 만에 세팅 끝내고 우수한 결과 내는 중

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서울신문

실시간 속보 '스마트폰도 없고 인터넷 못 믿어'…아날로그 한계 드러낸 日 백신 대책 #뉴스를 부탁해 | 서울신문기사 전체보기

DGIST 2020년도 하반기 '삼성미래기술육성사업' 2개 과제 선정

0 입력 : 2020-10-12 13:34 | 수정 : 2020-10-12 13:34

DGIST 에너지공학전공 양지웅 교수와 로봇공학전공 한상윤 교수가 삼성전자 미래기술육성사업이 지원하는 2020년도 하반기 소재기술, ICT 창의과제에 선정됐다.

가장 많이 본 뉴스 1~5 6~10

1 "중고차 사기로 죽음 당해" 60대 울분…靑 청원도 등장
2 "전자담배도 담배다"…실내흡연 금지 '임영웅법' 민…
3 코로나로 사망, 인도의 70대 여성 관엠에서 갑자기 …
4 공효진, '하의실종' 각선미 자랑
5 "XX아" 밥상 차려준 아버지 주먹질한 패륜 변호사

서울Eye : 포토뉴스 +

대구신문 2020년 10월 13일 화요일 014면 경제

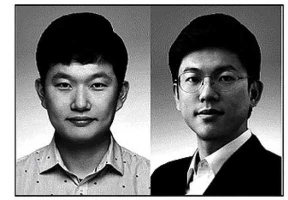
DGIST '삼성미래기술육성사업' 2개 과제 선정

양지웅·한상윤 교수 연구 "양자점 디스플레이 실용화 신약 개발 등 난제 해결 기대"

대구경북과학기술원(DGIST)은 에너지공학전공 양지웅 교수와 로봇공학전공 한상윤 교수가 삼성전자 미래기술육성사업이 지원하는 2020년도 하반기 소재기술, ICT 창의과제에 선정됐다고 12일 밝혔다.

DGIST에 따르면 양지웅 교수는 '양자점의 생로병사 비밀규명을 통한 고효율·고안정성 양자점 소재·소자 개발'이라는 연구주제로 이번 사업에 선정됐다. 해당 연구는 양자점 나노입자의 생로병사 전 과정에 대한 기초과학적 이해를 통해 고효율, 고안정성의 QLED 디스플레이 기술의 구현을 목표로 한다.

양 교수는 "양자점은 차세대 디스플레이 기술로 많은 주목을 받고 있지만 아직 합성 및 열화과정에 대한 근원적인 이해가 부족해 자발광 QLED의 효율 및 안정성이 낮은 상태"라며 "이번 과제를 통해 양자점 디스플레이 기술 실용화에 기여하는 연구를 수행하겠다"고 말했다.



DGIST 에너지공학전공 양지웅 교수(왼쪽)와 로봇공학전공 한상윤 교수. DGIST 제공

한상윤 교수는 '조합 최적화 문제를 위한 온 칩 광학 아이징 머신'을 연구주제로 이번 사업에 선정됐다. 빛이 흐르는 반도체를 이용해 양자영역에서 동작하는 인공신경망을 구현, 슈퍼컴퓨터로도 풀지 못했던 최적화 이론의 난제들을 실시간으로 푸는 초소형 칩을 개발하는 것이 연구 목표다.

한 교수는 "해당 칩이 개발되면 신약개발, 자율주행, 소셜네트워크, 암호화폐 등에 관련된 난제들을 시공간의 제약 없이 풀 수 있는 길이 열려 실생활에 눈에 띄는 파급효과가 생긴다"며 "이번 과제를 통해 인류의 삶에 긍정적인 변화를 가져오고 싶다"고 전했다.

삼성 미래기술육성사업은 삼성전자가 2013년 1조5천억원을 출연해 우리나라 미래 과학기술분야 연구를 10년간 지원하는 사회공헌 사업이다. DGIST 양지웅 교수와 한상윤 교수를 포함한 올 하반기 2차 선정과제는 기초과학 15개, 소재기술 7개, ICT 창의과제 분야 9개 등 총 31개 연구과제로 연구비 396억3천만원이 지원된다.

강나리기자 nnal2@idaegu.co.kr

- 재도약기
  - 학생분들 열정적이고 선해서 함께 신나게 연구하고 있음
  - 매우 도전적인 연구들 수행 중
  - <u>광 회로를 저전력으로 구현하는 것에는 감히 세계 최고라고 말할 수 있음</u>
- 다양한 기관들과 공동연구 진행
  - **EPFL, UC Berkeley, KAIST 등**

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CLEO 2021

16-Core Recirculating Programmable Si Photonic MEMS

Do Y. Kim[1], Young J. Park[1], Dong U. Kim[1], Myung S. Hong[1], Alain Y. Takabayashi[2], Youngjae Jeong[3], Jongwoo Park[3], Seungjun Han[3], Niels Quack[2], Kyoungsik Yu[3], and Sangyoon Han[*,1]

[1]*Department of Robotics Engineering, Daegu Gyeongbuk Institute of Science and Technology, Daegu 42988, Republic of Korea*
[2]*École Polytechnique Fédérale de Lausanne, STI IMT GR-QUA, Lausanne, 1015, Switzerland*
[3]*School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*
**E-mail address: s.han@dgist.ac.kr*

Abstract: We report on a 16-core recirculating programmable photonic array based on MEMS-tunable directional couplers. The photonic array has a compact footprint (0.04mm^2/cell) and negligible static power consumption. Waveguide-coupled single-ring resonators, CROWs, and add-drop filters are demonstrated. © 2020 The Author(s)

석사과정

DoYun Kim

석/박 통합 과정
(DGIST 학부 15학번)

YoungJae Park

CLEO 2021

Fully Reconfigurable Coupled-Resonator Optical Waveguides (CROWs) with 10 nW Static Power MEMS

Young J. Park[1], Dong U. Kim[1], Do Y. Kim[1], Myung S. Hong[1], Alain Y. Takabayashi[2], Youngjae Jeong[3], Jongwoo Park[3], Seungjun Han[3], Niels Quack[2], Kyoungsik Yu[3], and Sangyoon Han[*,1]

[1]*Department of Robotics Engineering, Daegu Gyeongbuk Institute of Science and Technology, Daegu 42988, Republic of Korea*
[2]*École Polytechnique Fédérale de Lausanne, STI IMT GR-QUA, Lausanne, 1015, Switzerland*
[3]*School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*
**E-mail address: s.han@dgist.ac.kr*

Abstract: We report on fully reconfigurable CROWs with MEMS-tunable waveguides. Resonator-to-resonator and resonator-to-waveguide coupling are fully tunable. Resonance of a resonator is also widely tunable to cover its full FSR. The static power consumption per tunable coupler is below 10nW. © 2020 The Author(s)

석/박 통합 과정
(DGIST 학부 15학번)

YoungJae Park

박사과정

Dong Uk Kim

- 연구실 시작 1년 만에 3편의 논문 국제 저명 학회에 채택
- **CLEO 2편 (세계 최고 권위 광학회, 구글 I5 index 기준)**
- **OFC 1편 상위 10% 논문 선정 (세계 최고 권위 광통신 학회)**

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OFC 2021

Not disclosed yet

박사과정

Dong Uk Kim

학/석 연계과정
(DGIST 학부 16학번)

MyeongSeok Hong

- 연구실 시작 **1**년 만에 **3**편의 논문 국제 저명 학회에 채택
- **CLEO 2**편 **(**세계 최고 권위 광학회**,** 구글 **I5 index** 기준**)**
- **OFC 1**편 상위 **10%** 논문 선정 **(**세계 최고 권위 광통신 학회**)**

풍족한 과제 수주, 유수 기관들과 협업

<KAIST>
- Prof. Kyoungsik Yu
- Youngjae Jeong
- Jongwoo Park
- Seungjun Han

<EPFL>
- Prof. Niels Quack
- Alain Y. Takabayashi

<DGIST>

KIST | CQI Center for Quantum Information

기본연구사업

SAMSUNG

삼성미래기술육성사업

NRF 한국연구재단

미래국방혁신기술개발사업

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정착지원금

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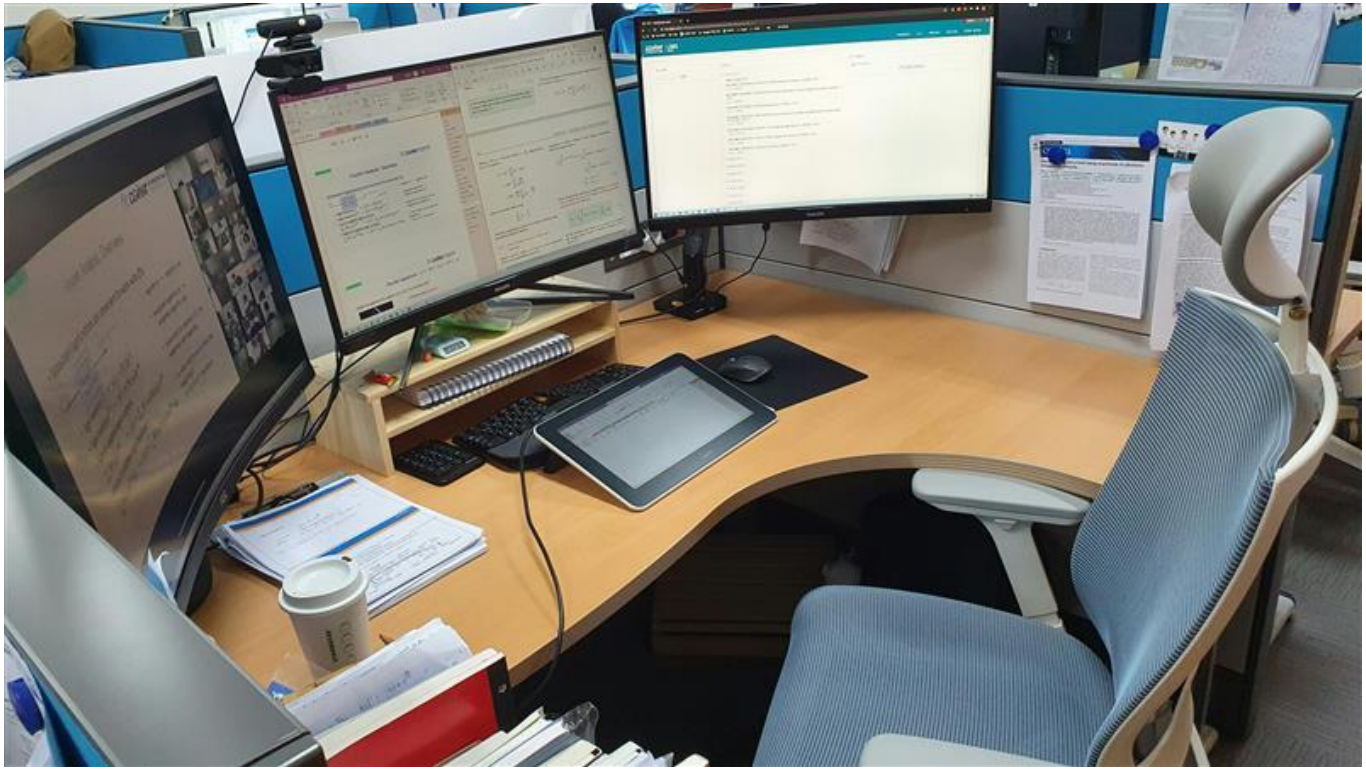
학/석 연계과정 홍명석 학생 연구실 자리



- 연구는 사람이 하는 것, 사람이 가장 중요한 자원. 연구에 집중 할 수 있는 환경 조성 노력.
- 스타트업 패키지 for 석사, 박사, 학/석연계 과정 (학부연구생은 기간에 따라 세팅)
- 학회 참가 기회 제공
  - 학부 연구생도 1저자로 top conference 논문 쓸 경우 해외 학회 참가비 전액 지원

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학부 연구생, 대학원생 절찬리 모집 중

shenaniganblog.com

- 학부연구생도 **SCI** 논문 저자 참여 가능
    - **1**년 이상 연구 시 **1**저자도 가능
- 학**/**석 연계과정 가능 **(**학부 **3**학년 때 지원**)**
    - **5**년에 학사**+**석사학위 취득
    - **SCI** 논문 **1**저자로 **2~3**개 이상 쓰는 것 가능
- 석사**,** 박사 과정도 절찬리 모집 중

- **Office hour**
    - 월**/**수**/**화**/**목 오후 **4**시**~5**시**, E5 308**호
    - 진로상담 **(**유학**,** 대학원 진학**,** 취업 등**)** 가능
    - 학업상담 가능
    - 저의 대학생활 경험 썰 풀어드림

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OFC 2021

8×8 Programmable Multi-Beam Pattern Projection Based on Multicast Silicon Photonic MEMS Switches

Dong U. Kim[1], Myung S. Hong[1], Do Y. Kim[1], Young J. Park[1], Alain Y. Takabayashi[2], Youngjae Jeong[3], Jongwoo Park[3], Seungjun Han[3], Niels Quack[2], Kyoungsik Yu*[,3], and Sangyoon Han[,1]**

[1]Department of Robotics Engineering, Daegu Gyeongbuk Institute of Science and Technology, Daegu 42988, Republic of Korea
[2]École Polytechnique Fédérale de Lausanne, STI IMT GR-QUA, Lausanne, 1015, Switzerland
[3]School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea
**ksyu@kaist.edu, **s.han@dgist.ac.kr*

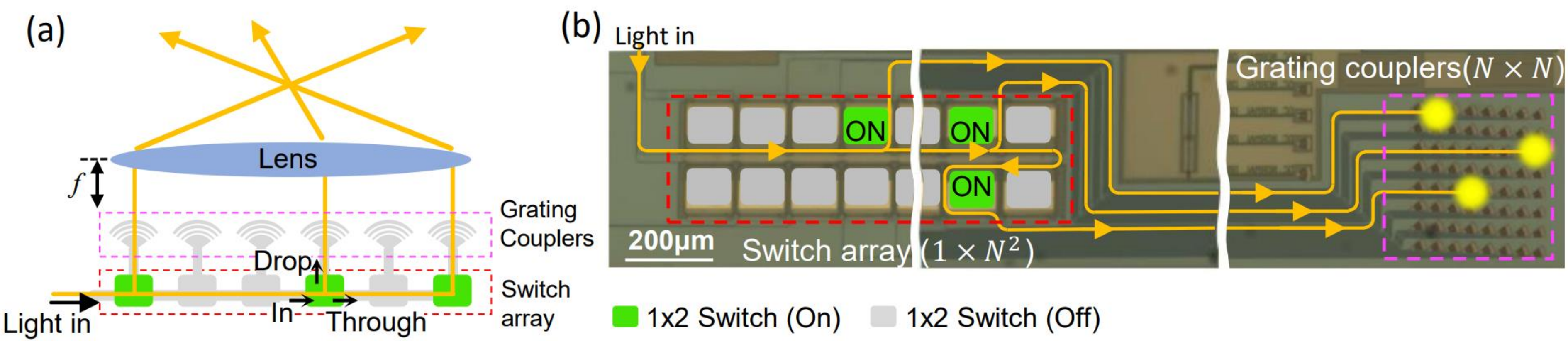
Abstract: We present an arbitrary 8×8 beam pattern projection system based on a programmable grating coupler array with a Fourier lens. The static power consumption and the reconfiguration time are below 1μW and 10μs, respectively. © 2021 The Author(s)

박사과정

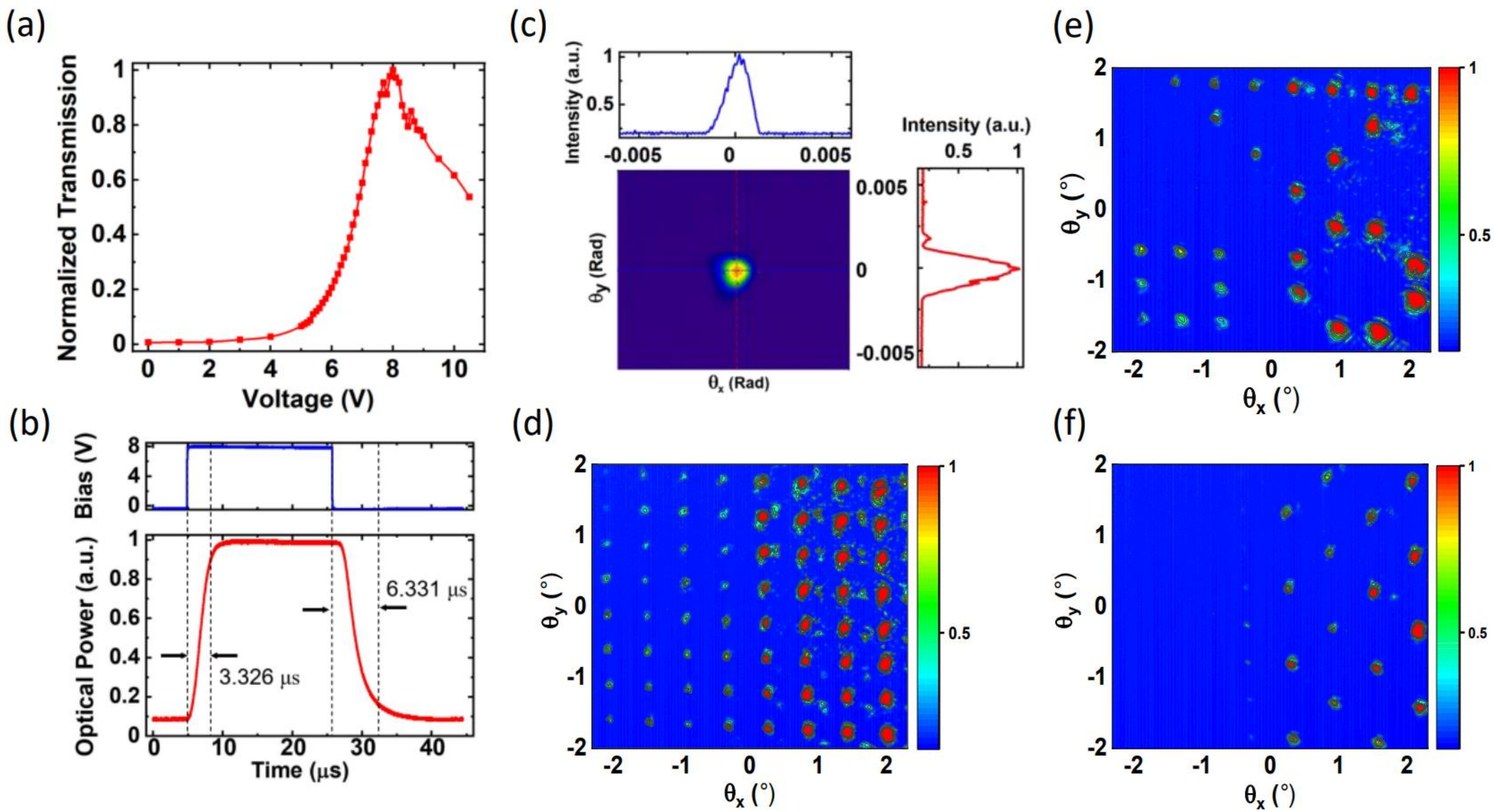
Dong Uk Kim

학/석 연계과정
(DGIST 학부 16학번)

MyeongSeok Hong



- **OFC(세계 최고 광통신 학회) 상위 10% 논문 선정 (세계 최고 권위 광통신 학회)**
- **KAIST 및 EPFL (스위스)과 공동연구**


(a)
Normalized Transmission
Voltage (V)
(b)
Bias (V)
Optical Power (a.u.)
Time (μs)
3.326 μs
6.331 μs
(c)
Intensity (a.u.)
-0.005
0
0.005
θy (Rad)
θx (Rad)
(d)
θy (°)
θx (°)
(e)
θy (°)
θx (°)
(f)
θy (°)
θx (°)

Chip image