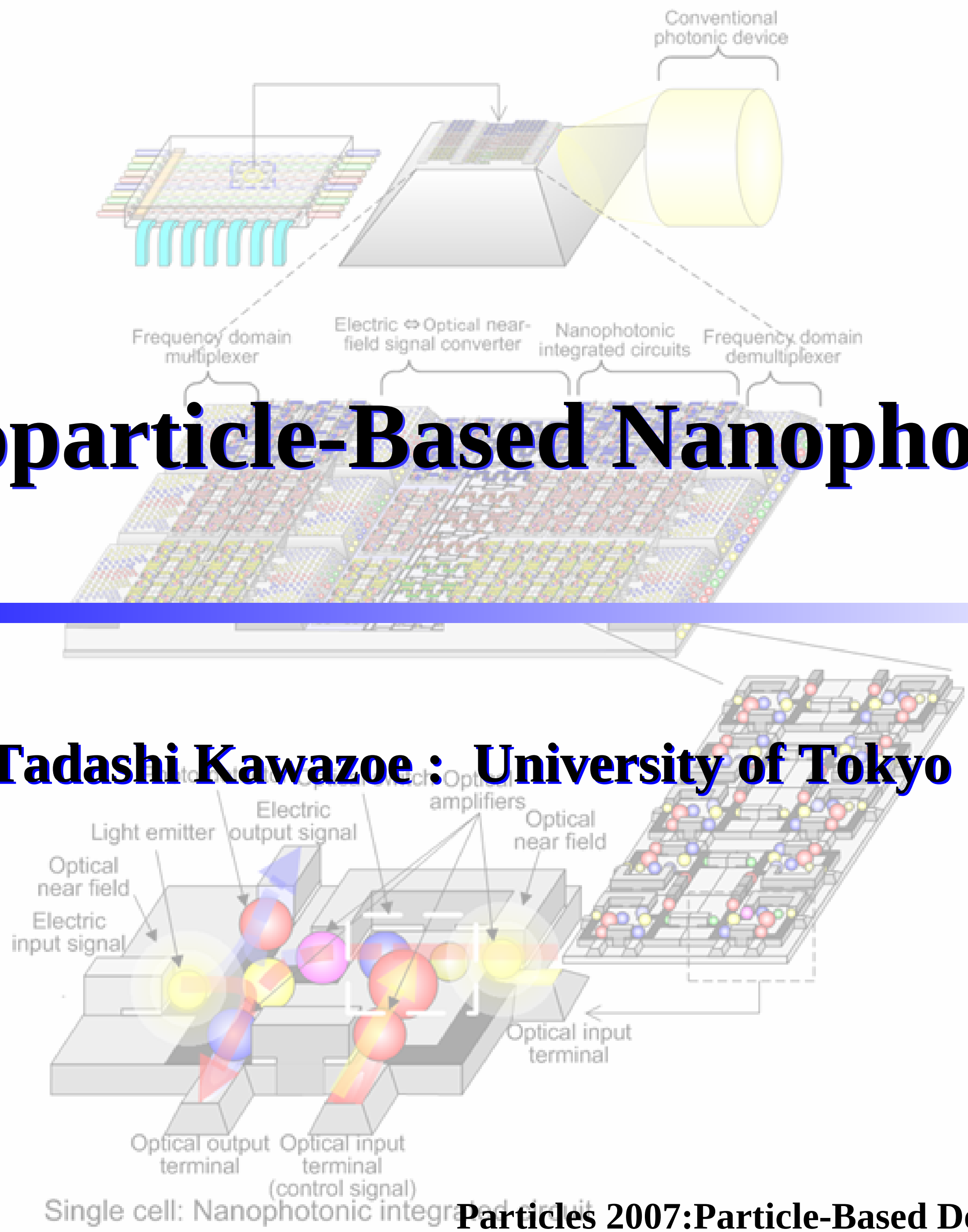
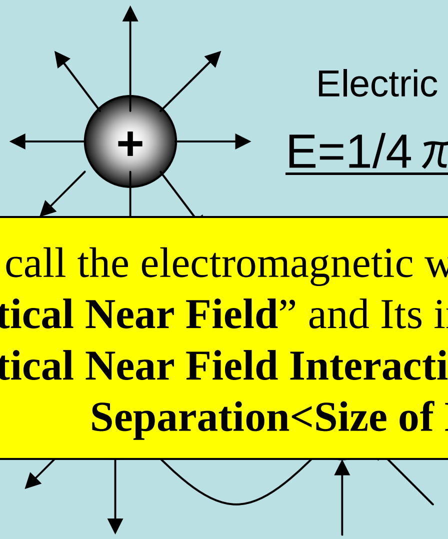
Nanoparticle-Based Nanophotonics



Tadashi Kawazoe : University of Tokyo

Optical Near-Field

Electric Field & Interaction by Charges



Electric Field

$E=1/4\pi k(q/r^2)$

•We call the electromagnetic wave in this region "**Optical Near Field**" and Its interaction is called "**Optical Near Field Interaction**".

Separation<Size of Dipole

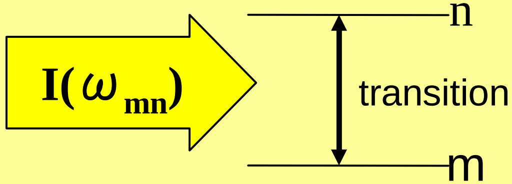
Coulomb force

$F=Eq=1/4\pi k(q^2/r^2)$

•These equations are exact for every distances, when we do not consider their wave function. Because this equation is the definition of charge.

Electric Field & Interaction by Dipoles

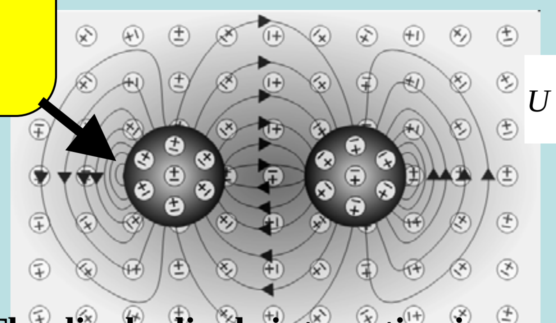
Propagating light



$W_{mn}=4\pi^2 I/\hbar c \cdot \boldsymbol{p}_{mn}^2$

p_{mn}: (transition) electric dipole

e obtained p_{mn} as a physically material parameter by
g this relation from the experimental results.

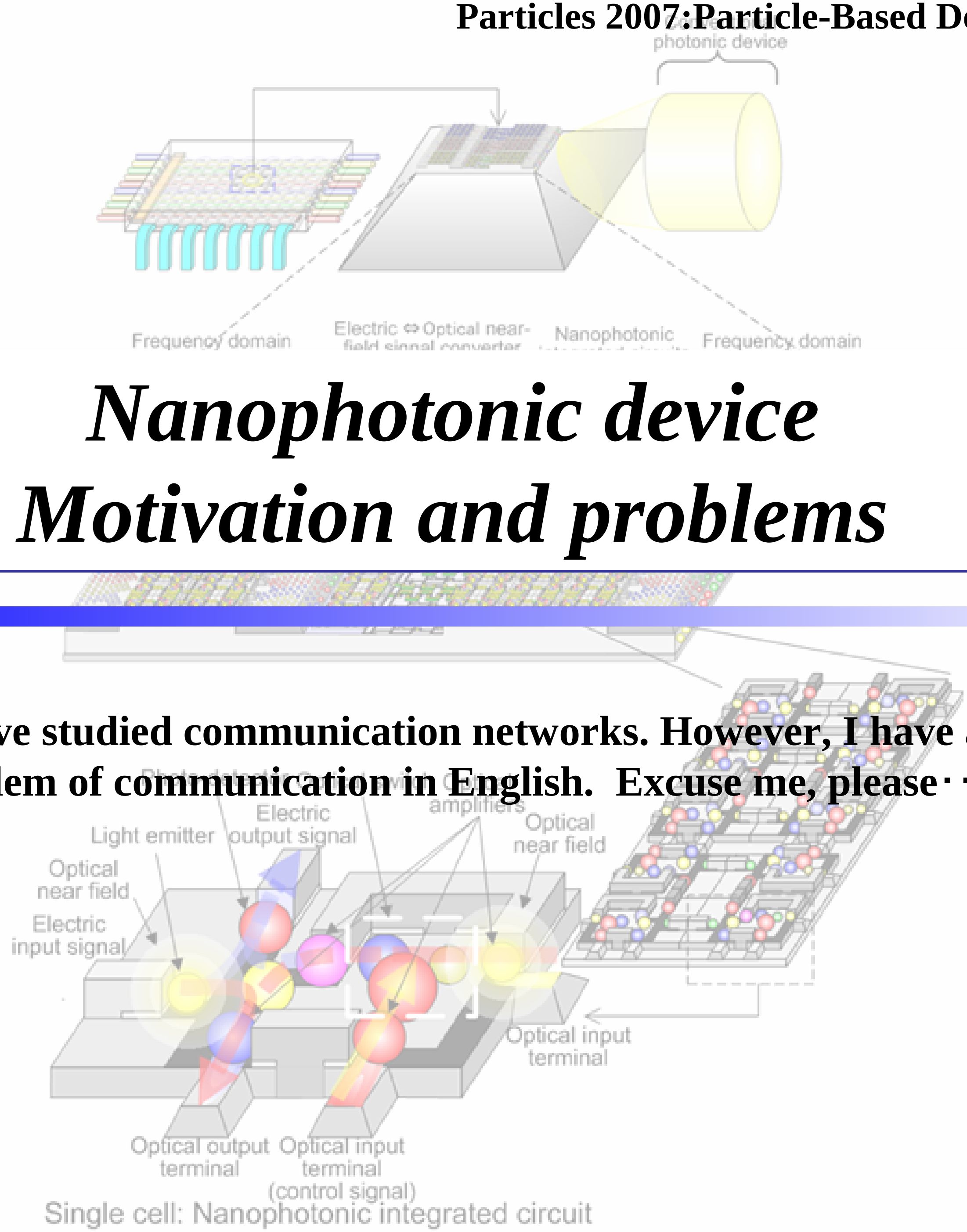


$$U=\frac{(\boldsymbol{p}_1\cdot\boldsymbol{p}_2)r^2-3(\boldsymbol{p}_1\cdot\boldsymbol{r})(\boldsymbol{p}_2\cdot\boldsymbol{r})}{r^5}$$

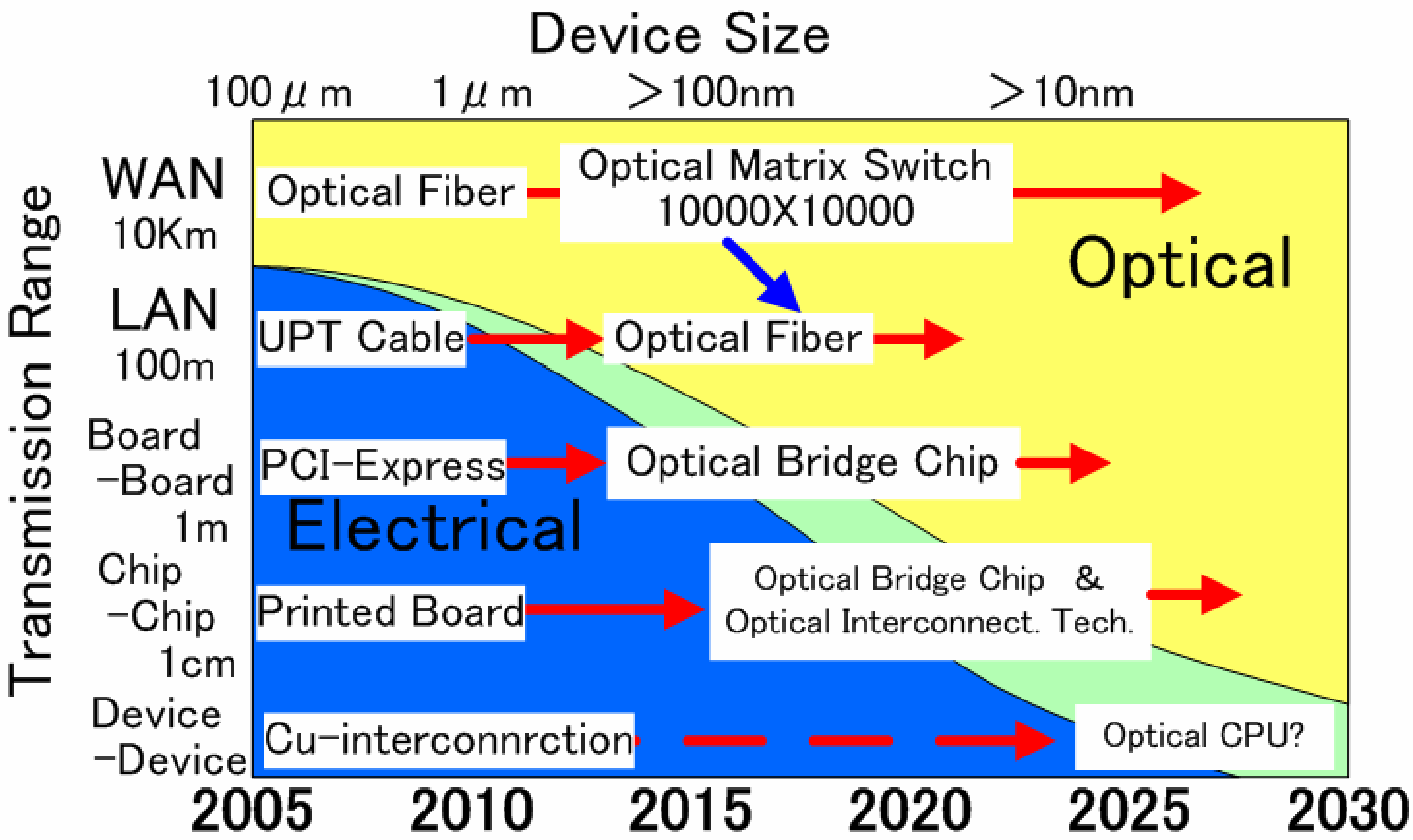
•The dipole-dipole interaction is correct in nano-region? When the separation of dipoles are broad, it is exact. Because one acts as light emitter and another acts as absorber. However, when it is narrow, the dipoles change and the dipole-dipole interaction also changes. Thus the equation of dipole-dipole interaction should change in nanometric region.

Nanophotonic device Motivation and problems

•I have studied communication networks. However, I have a problem of communication in English. Excuse me, please‥‥‥.

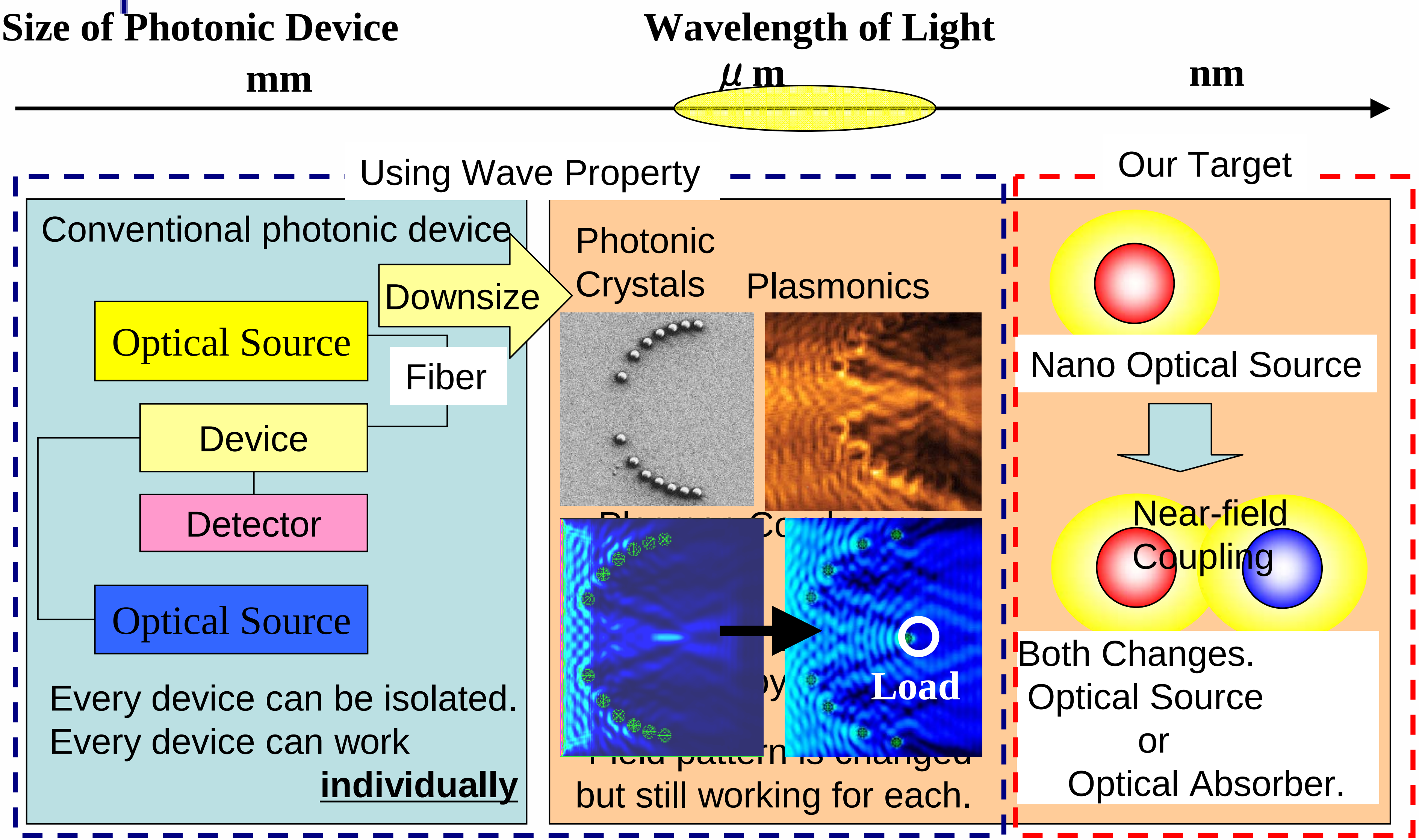


Technology roadmap of optical devices

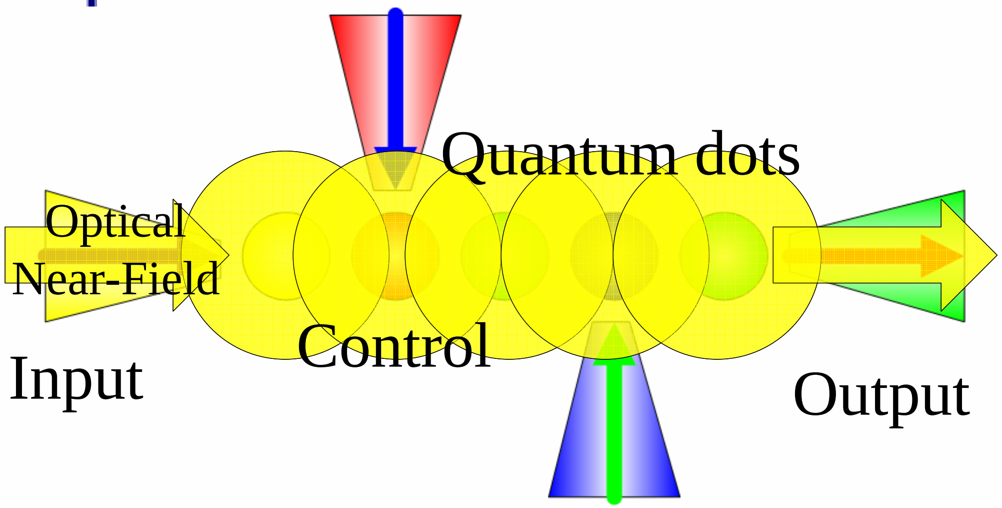


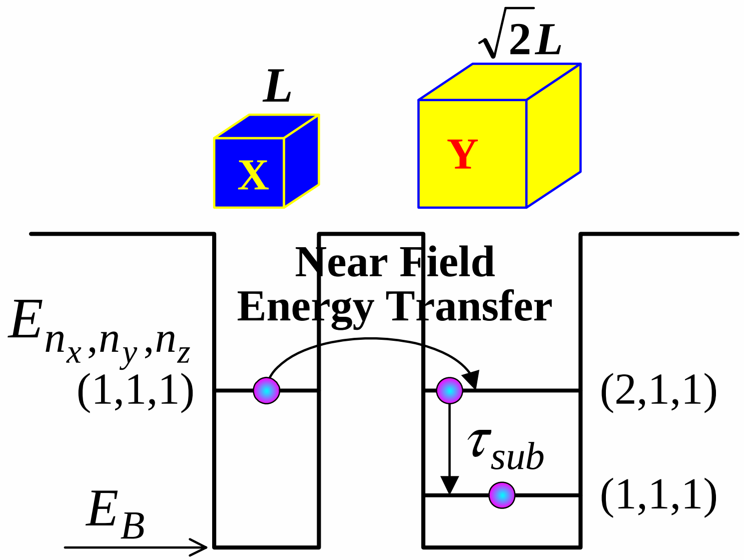
※**MIT** ***Microphotonics Center***: Communications Technology Roadmap 2005

Connections between nanometric device



Energy Transfer for Nanophotonic Device





Schematic Image of Nanophotonic Device

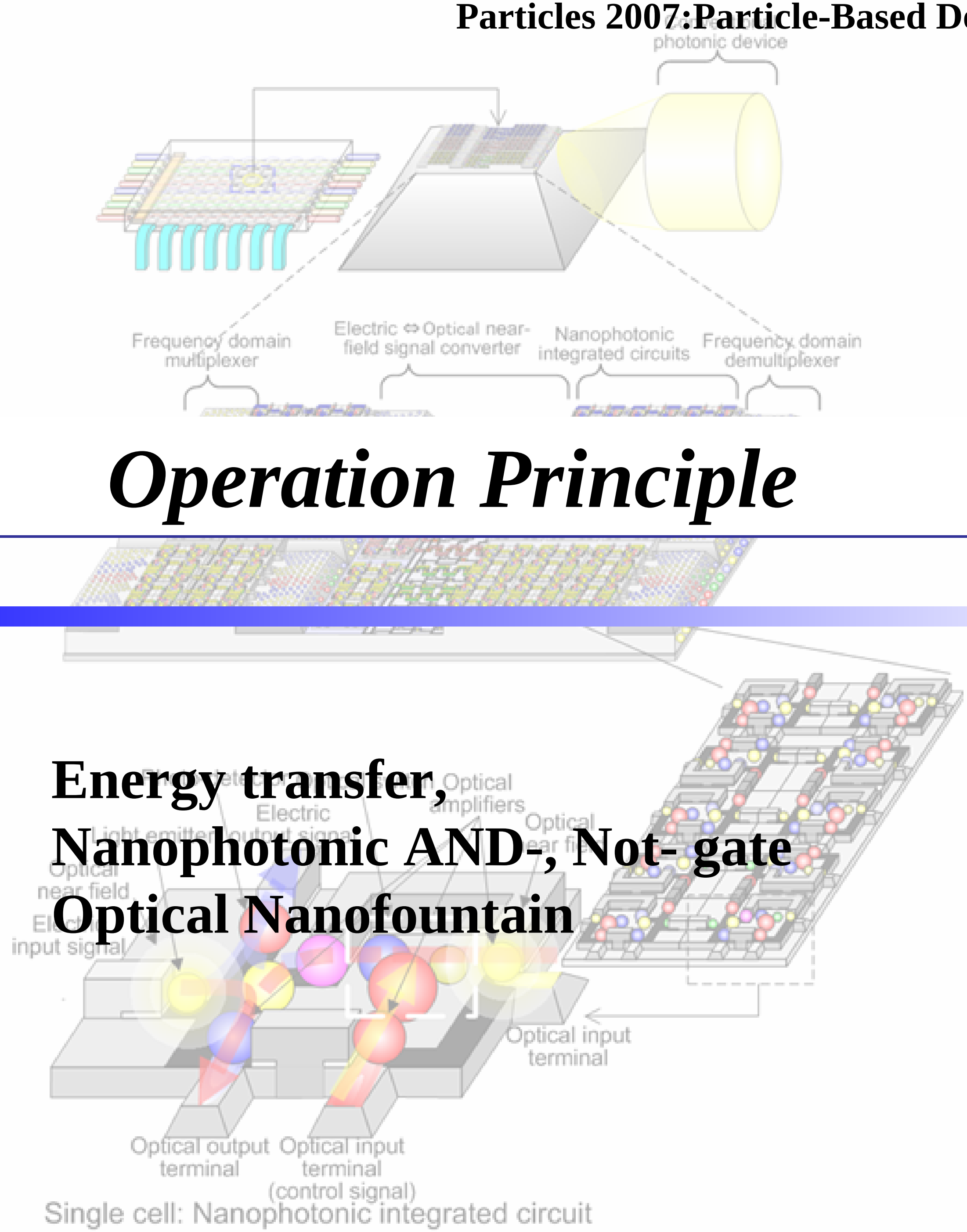
Unidirectional signal transfer is necessary in order to use ONF as a signal carrier.

1. How to use the optical near field as a signal (energy) carrier.
→The energy dissipation of the sublevel transition is applicable to realize the unidirectional signal transfer, which will be shown in the next page.

2. How to control the signal.
→We proposed several QDs-systems to control the signal transfer, which will be mentioned later.

Operation Principle

Energy transfer,
Nanophotonic AND-, Not- gate
Optical Nanofountain

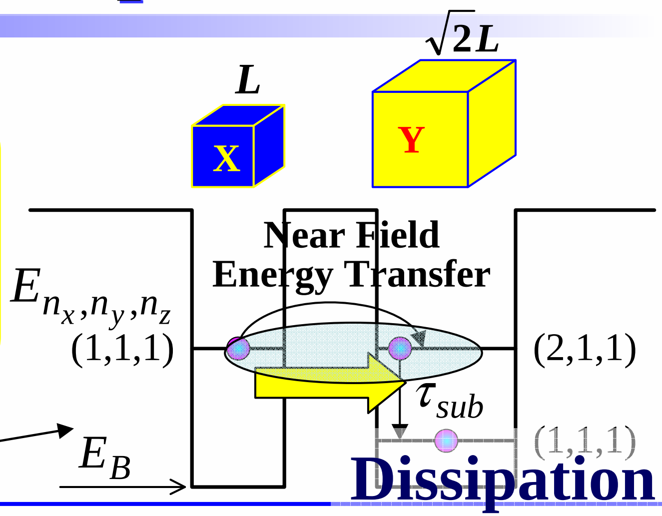


Energy transfer between quantum dots

Confinement energy of carriers in a quantum cube

$$E(n_x, n_y, n_z) = \frac{\hbar^2 \pi^2}{2m}\left(\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2\right)$$

$$\tau_{\text{lifetime}} > \tau_{\text{transfer}} > \tau_{\text{sub}}$$

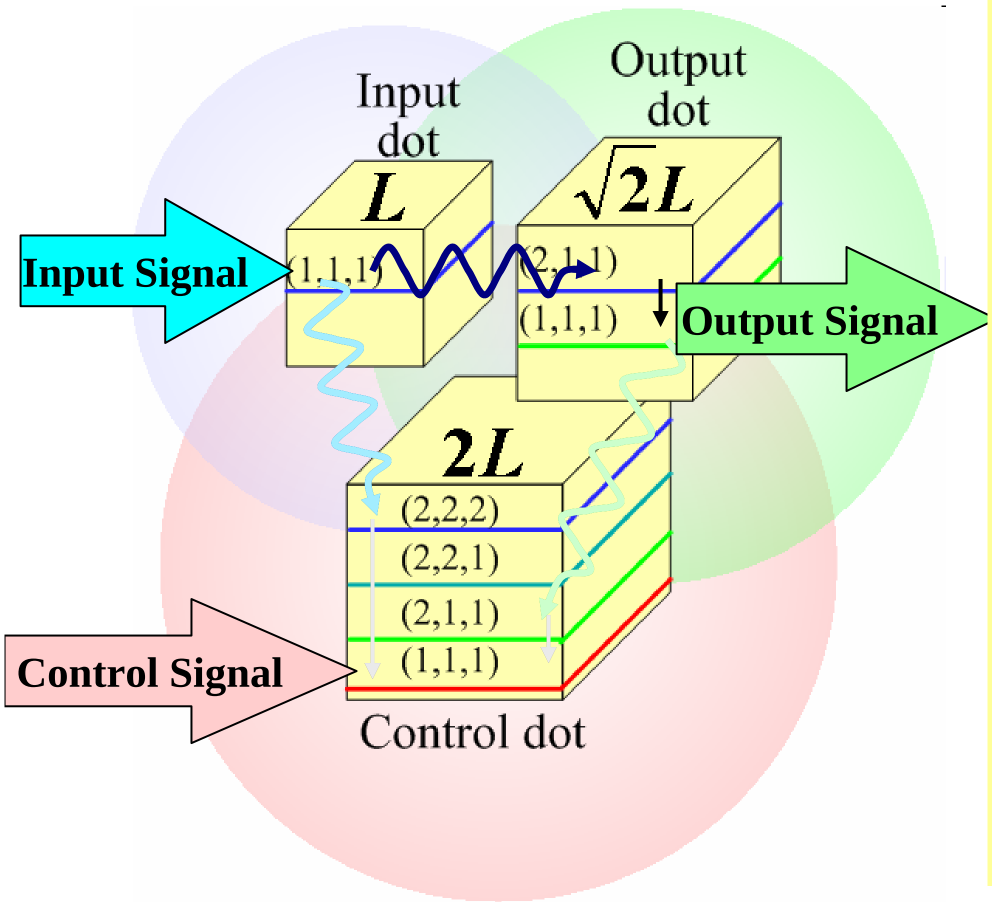


- In the quantum cubes, the carriers are quantized and their discrete energy levels are given by this simple equation.
- When two quantum dots with Size Ratio=1: $\sqrt{2}$ are closely spaced, the strong near-field interaction couples these resonant energy levels (1,1,1) and (2,1,1).
- In the larger quantum dots, the energy relaxation to the lowest energy sublevels is very fast.
- This small energy dissipation disturbs the back-transfer to the smaller QD.
- Then, the energy transfer occurs from the smaller to the larger quantum dot.
- Thus, the optical near filed obtains the ability as a signal carrier.

T. Kawazoe, et al., Phys. Rev. Lett. 88, 067404 (2002).

How to control the signal.
1.Nanophotonic Switch.(AND-Gate)

ON State



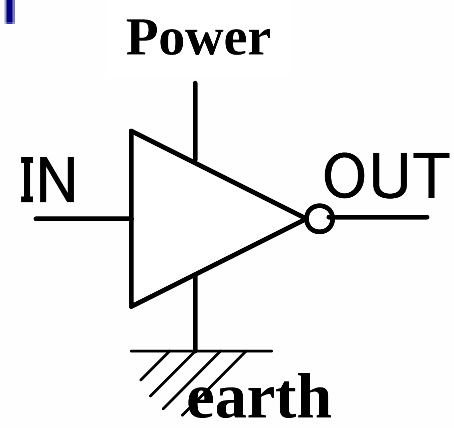
•For the switching operation, we consider three closely spaced cubic quantum dots with Size Ratio $=1:\sqrt{2}:2$.

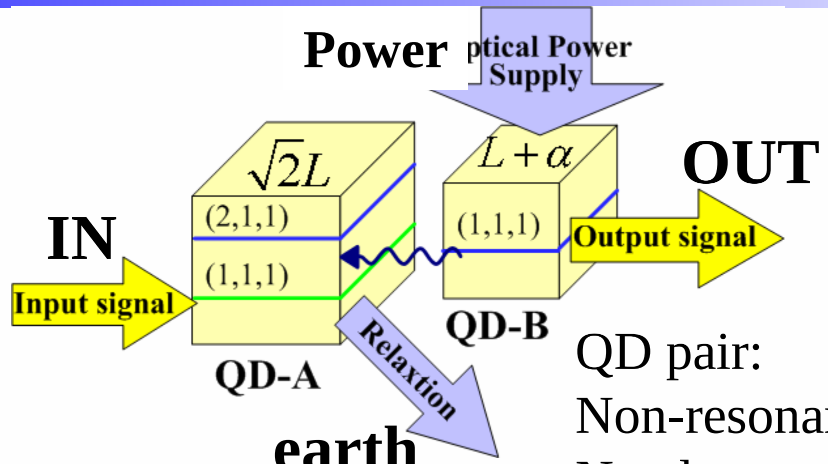
•In the **OFF** operation, the input energy escapes to the control dot, and then the output signal is obstructed.

•In the **ON** operation, the escape paths are blocked by the excitation of the control dot, and then the input energy goes through the output dot giving an output signal.

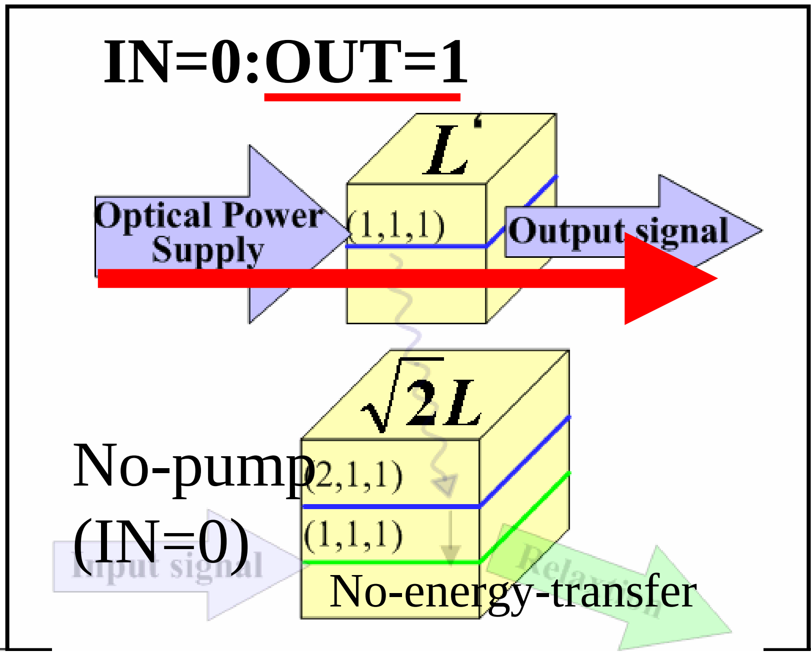
•Thus, the nanophotonic switch is realized.

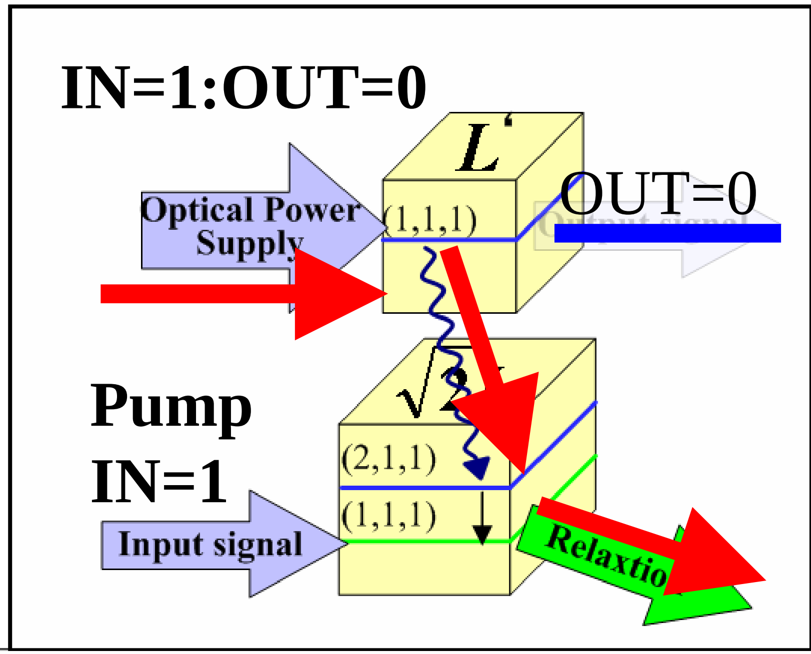
2.Nanophotonic NOT-Gate



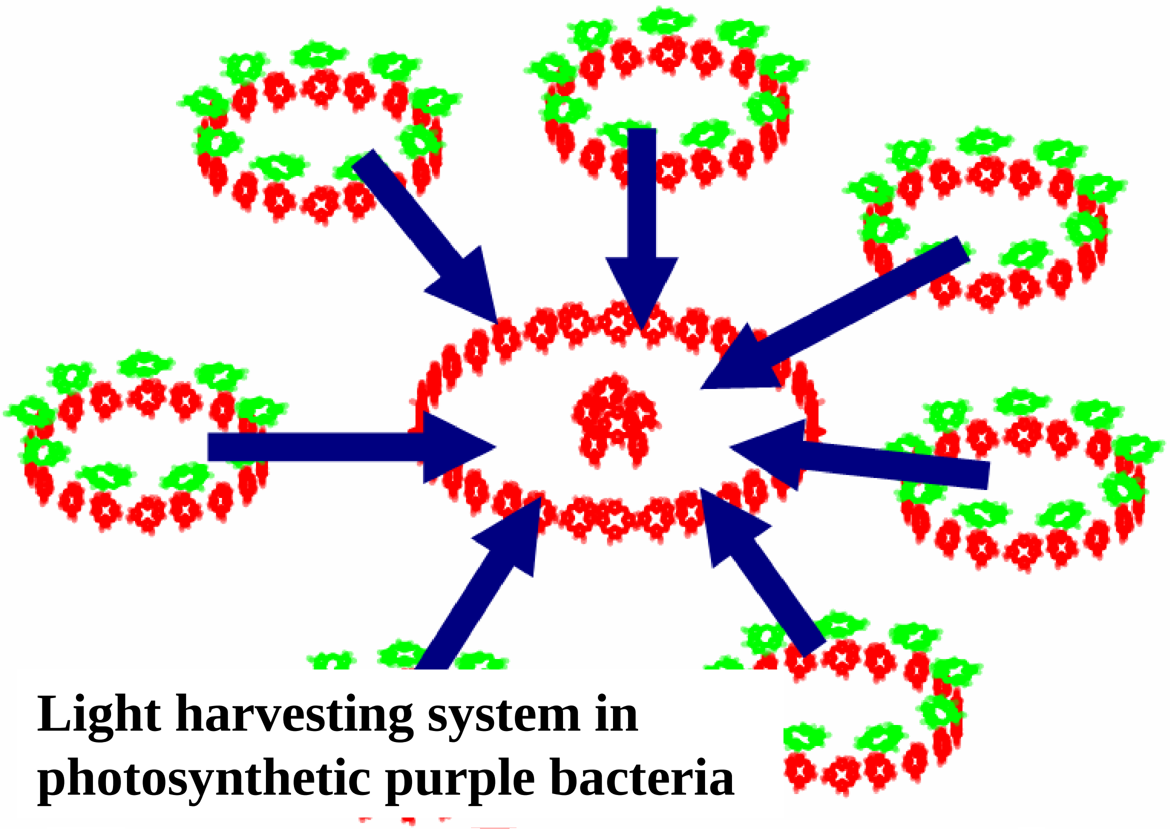


QD pair:
Non-resonant with each other.
Nearly resonant.





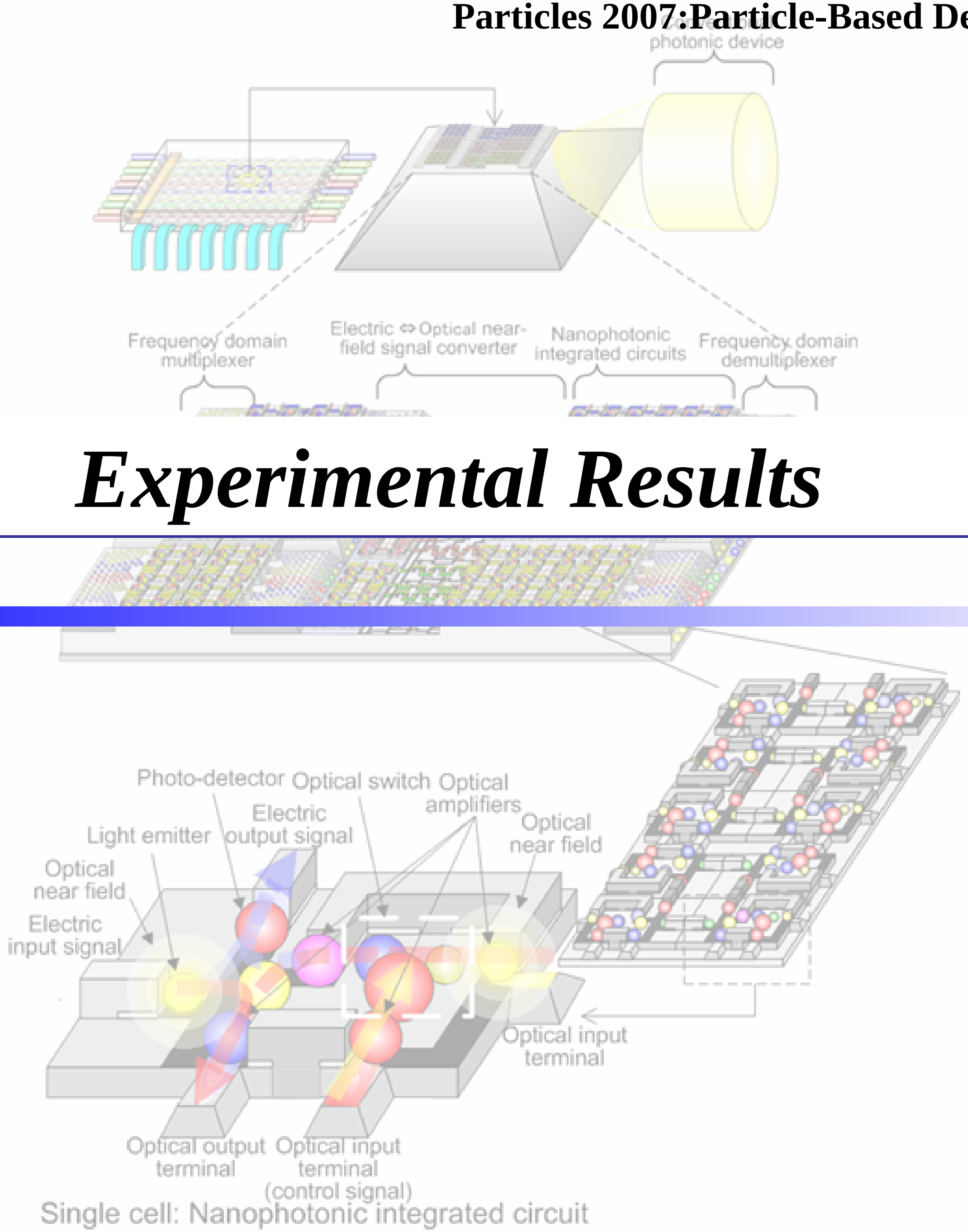
3.The optical nano-fountain using energy transfer between quantum dots



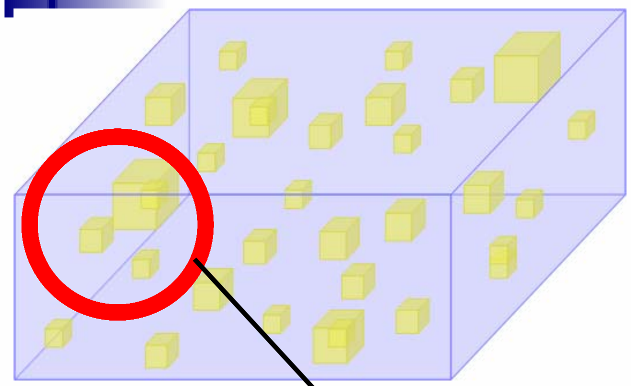
Light harvesting system in photosynthetic purple bacteria

The energy transfer between quantum dots is similar to the energy transfer in the light harvesting system in photosynthetic purple bacteria. (small to large).

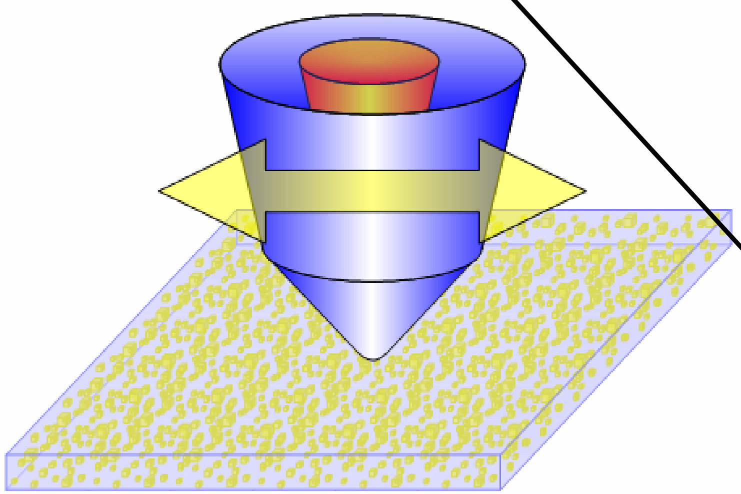
Experimental Results



Sample for Device Operation CuCl QDs in a NaCl Matrix



CuCl Quantum Cube in a NaCl Matrix



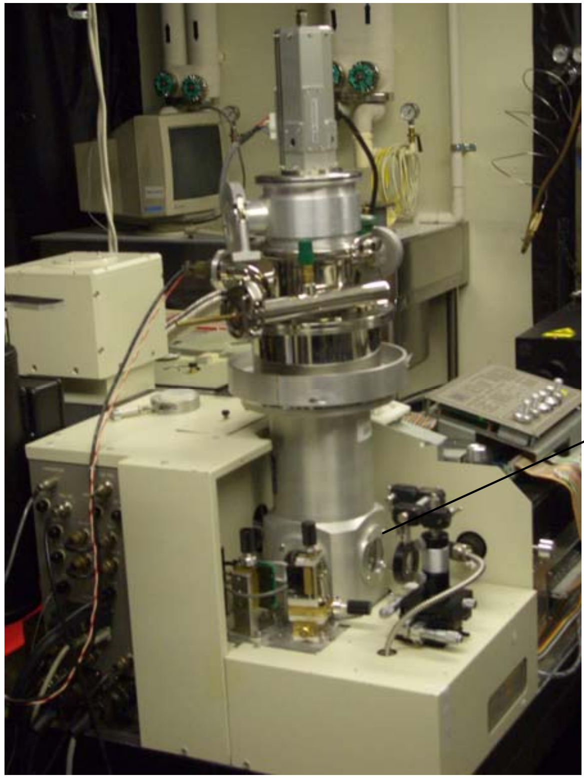
Near-Field Optical Microscopy

- High density of quantum dots.
- Deep potential depth.
- Nearly perfect cubic shape.

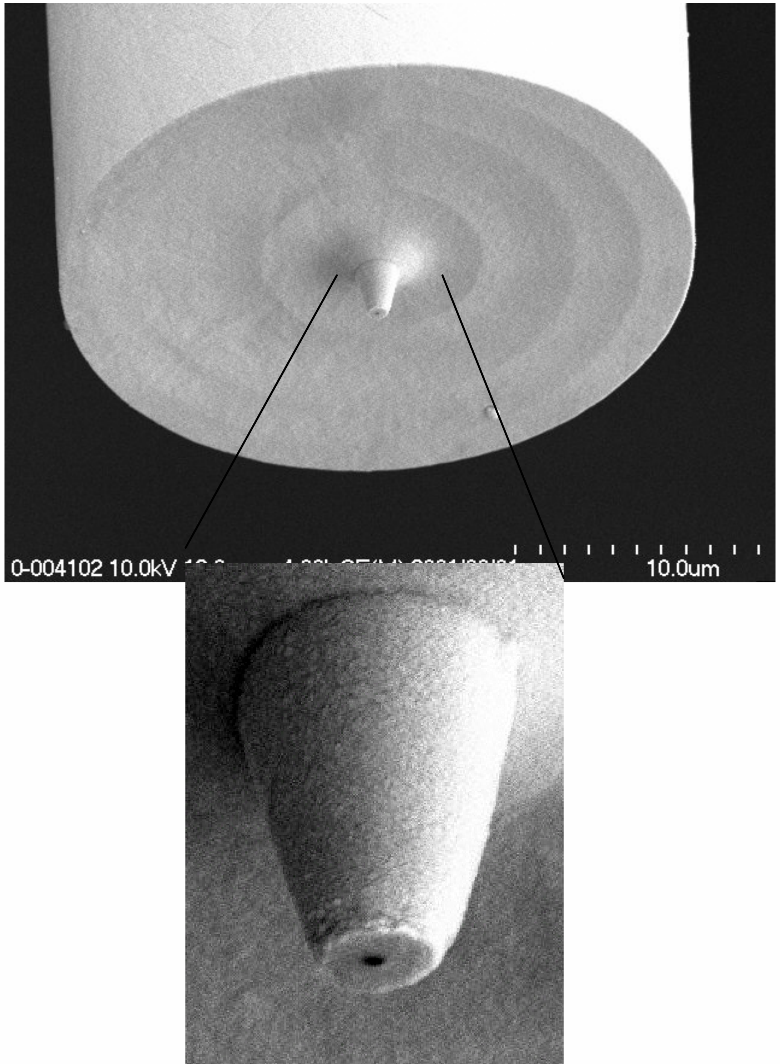
For verifying the operation principle of the nanophotonic devices, we selected the material of cubic CuCl quantum dots embedded in a NaCl matrix.

For this sample, the first essential task is to search the coupled quantum dots acting as the nanophotonic devices from the inhomogeneous size dispersed 'sea'.

Optical Near-Field Microscope

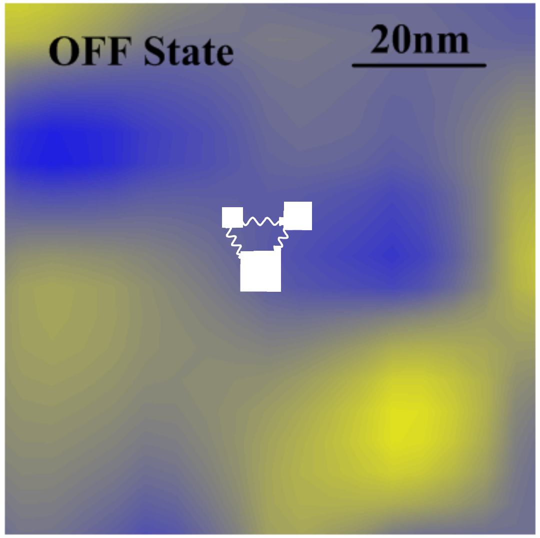


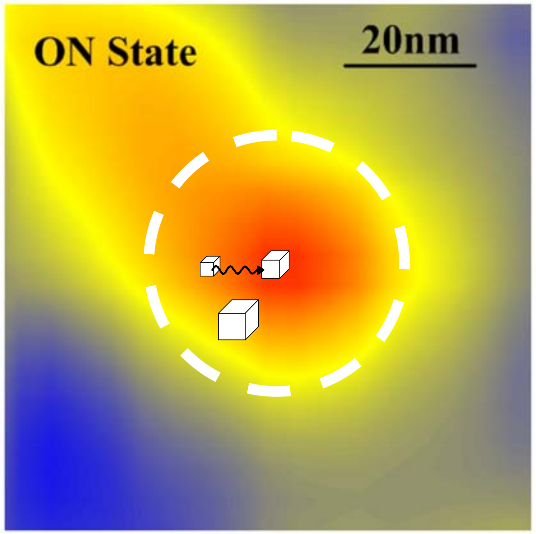
JASCO Co. LTD. :SNOM

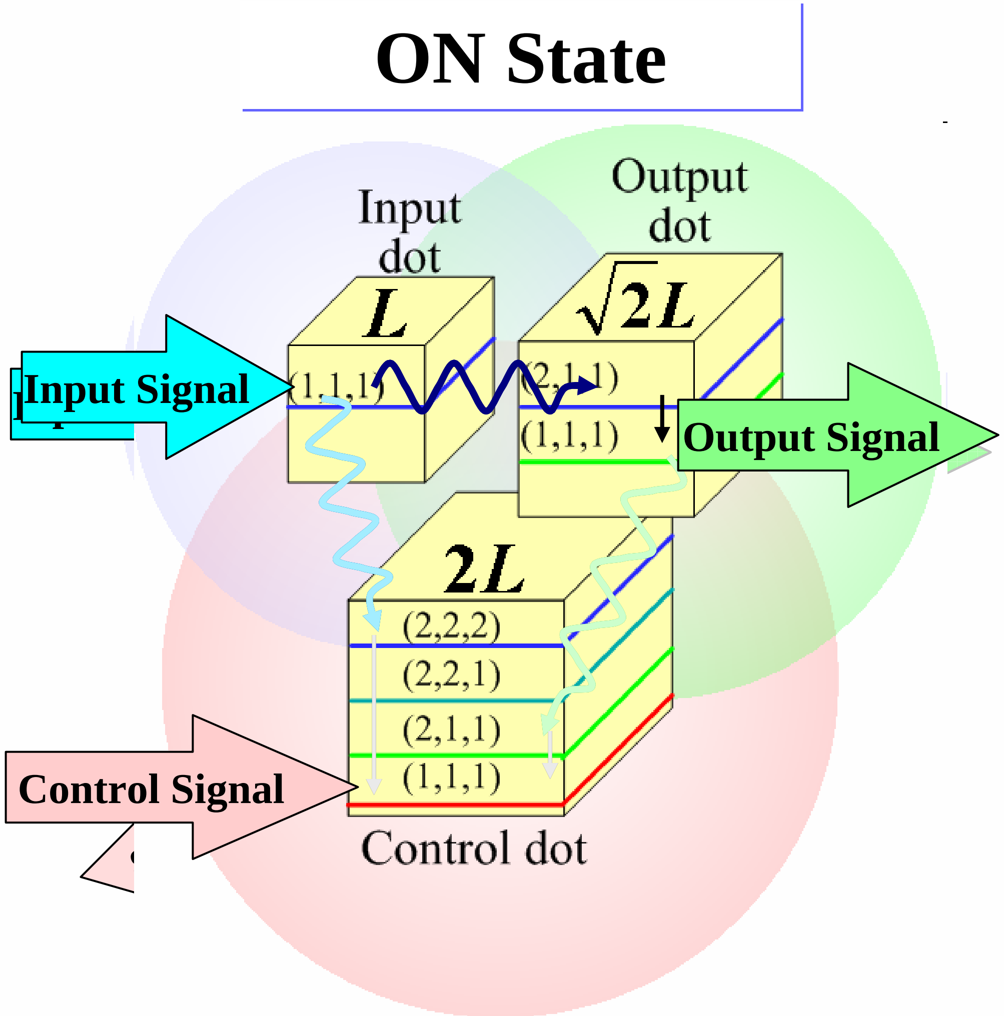


500nm

Experimental results: 1. Nanophotonic Switch

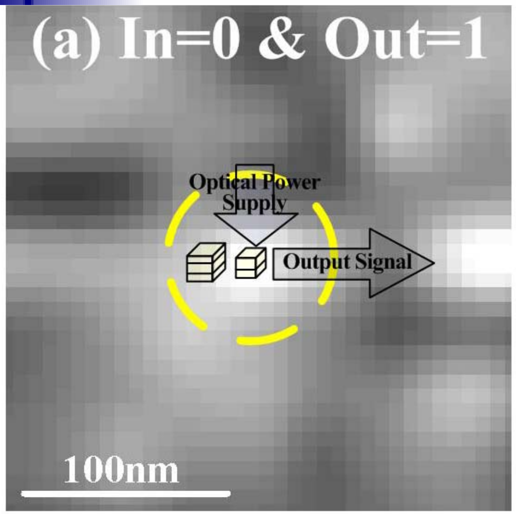


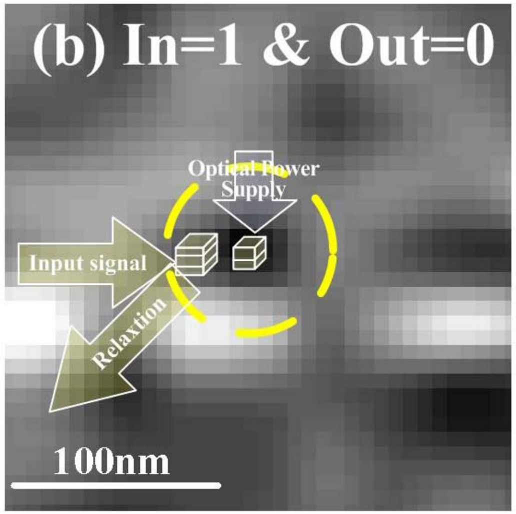


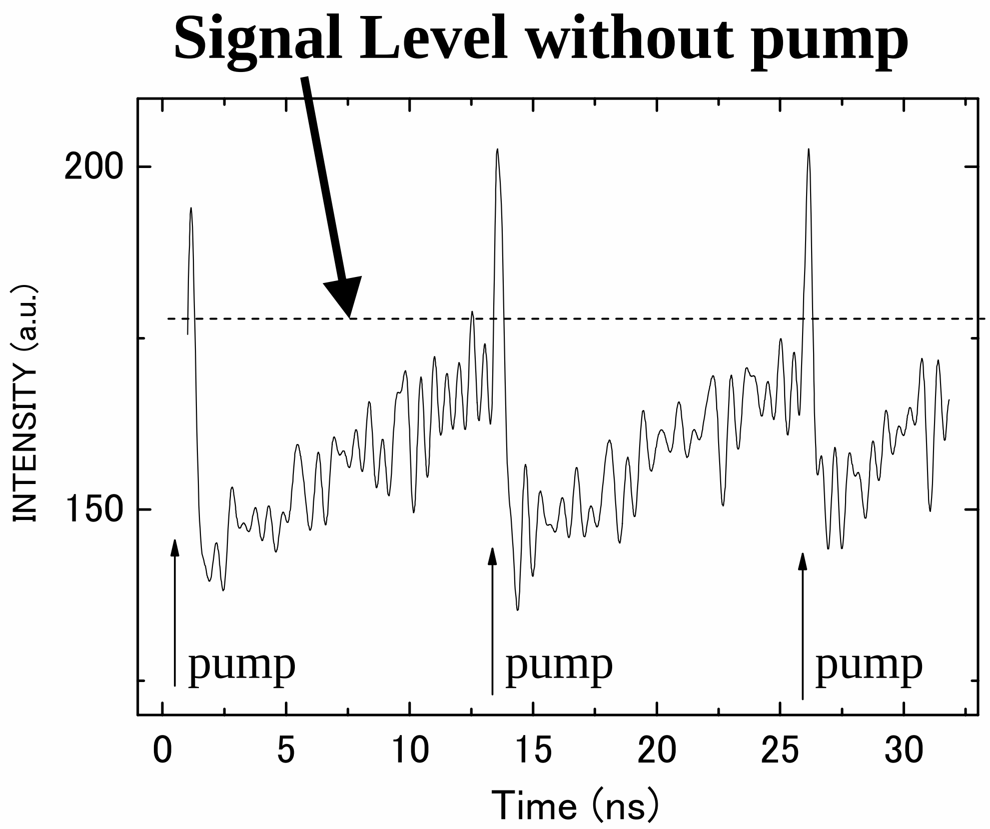


T.Kawazoe et al., Appl. Phys. Lett. 82, 2957(2003).

Experimental Results: 2.NOT-Gate







These experimental results show this coupled quantum dots system is acting as nanophotonic **NOT-gate**.

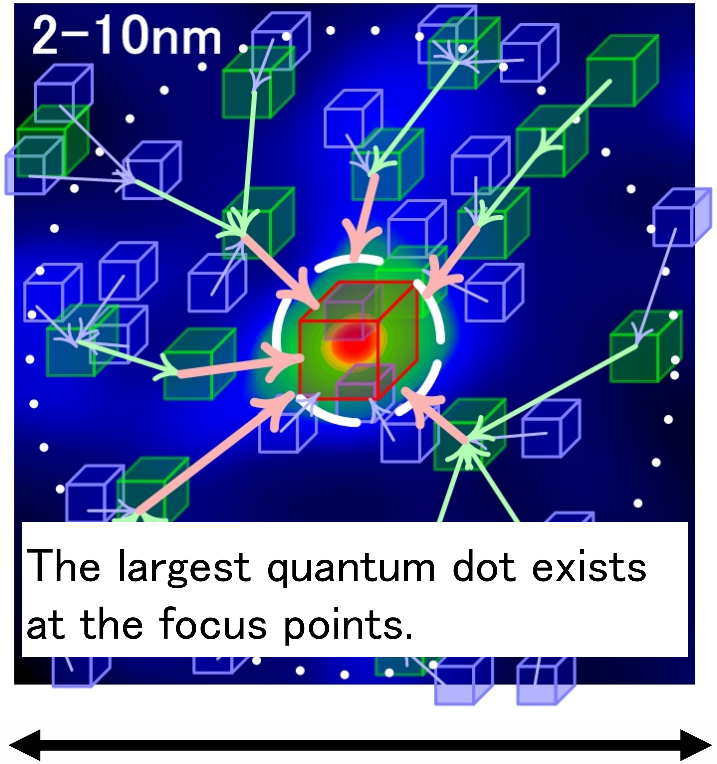
Applied physics B Vol. 84, No.1-2,(2006).

Experimental Results: 3. Nano-fountain

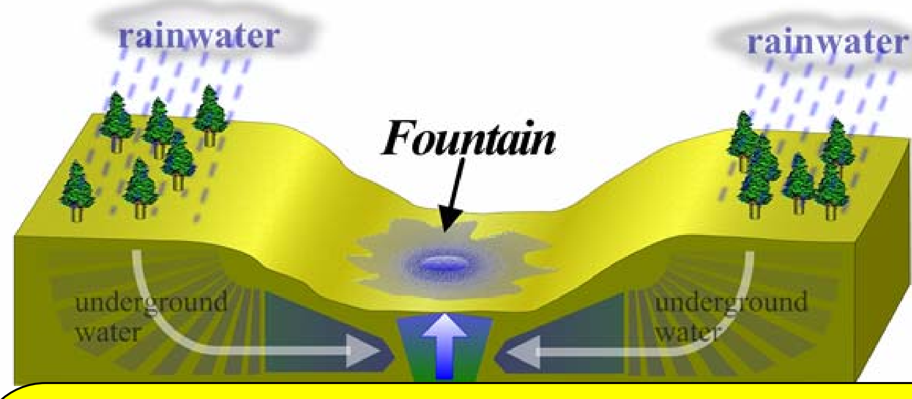
Optical nano-fountain

Appl. Phys. Lett. **86** 103102 (2005).

Intensity Distribution



The many middle and small sized quantum dots exist at around the focusing position.



The excitation energy concentrate the largest quantum dot via optical near-field energy transfer.

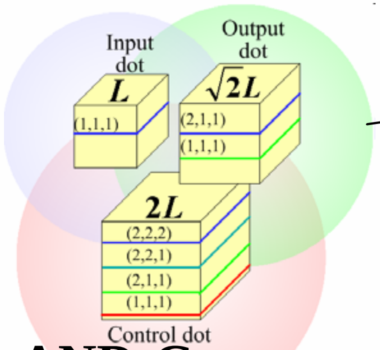
The focus diameter was 10 nm.

It corresponds to NA≅40

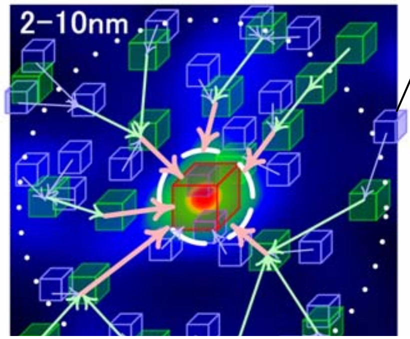
The observed luminescence intensity was as five times large as luminescence intensity of the isolated single quantum dot.

Optical Content Addressable Memory

Combination of And-gate and Nano-fountain realizes Optical CAM. (Output= Σ A･B): *Opt. Lett., Vol. 30, No.2, 201-204, (2005).*

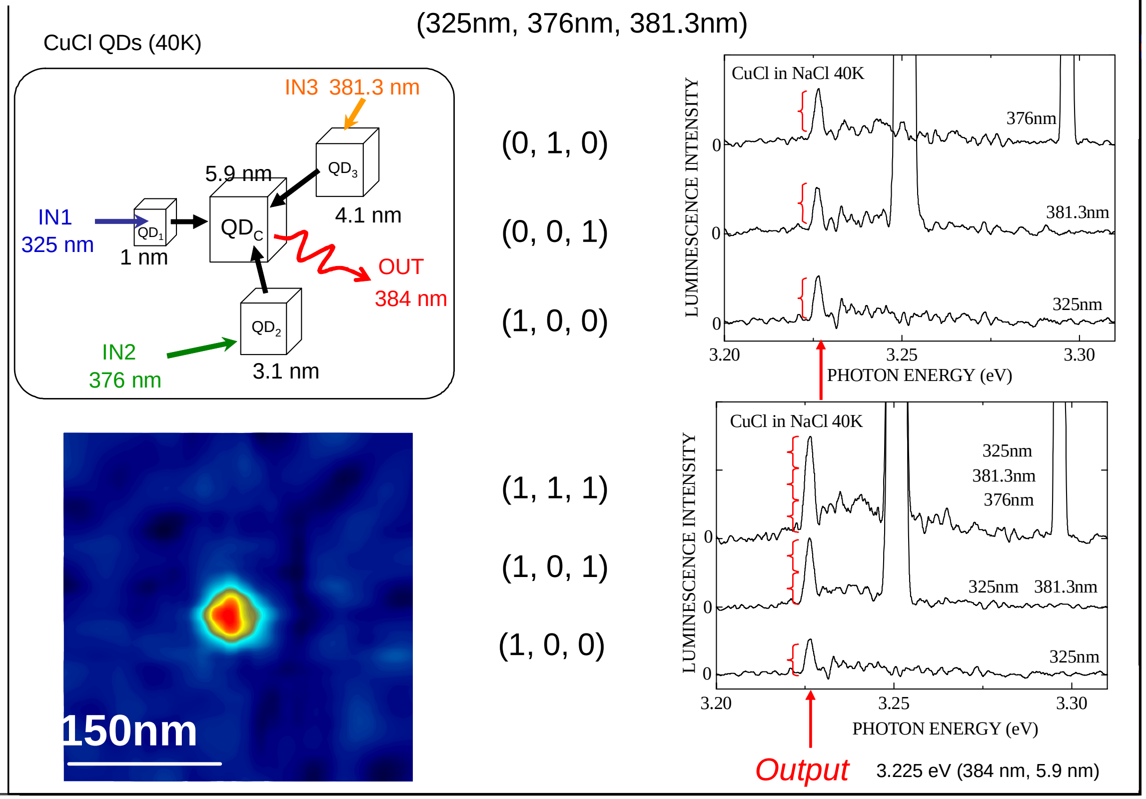


AND-Gate



Optical Nano-fountain

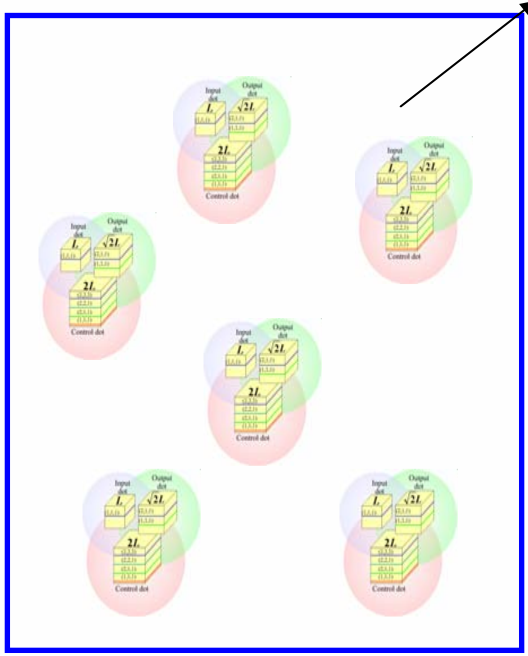
Optical Content Addressable Memory



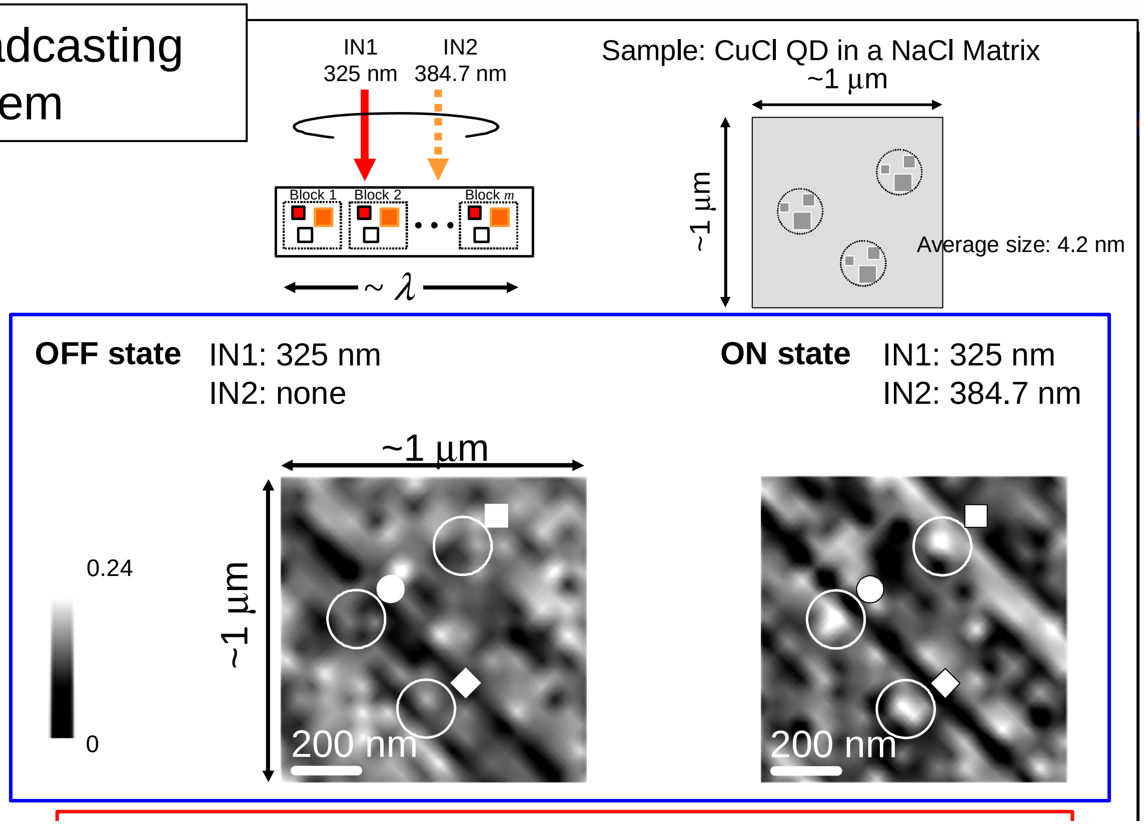
Broadcasting system

Many AND-gates can act as broadcasting system, which delivers the data to many Receivers. :Opt. Express, Vol. 14, 306-313 (2006).

Broadcasting System

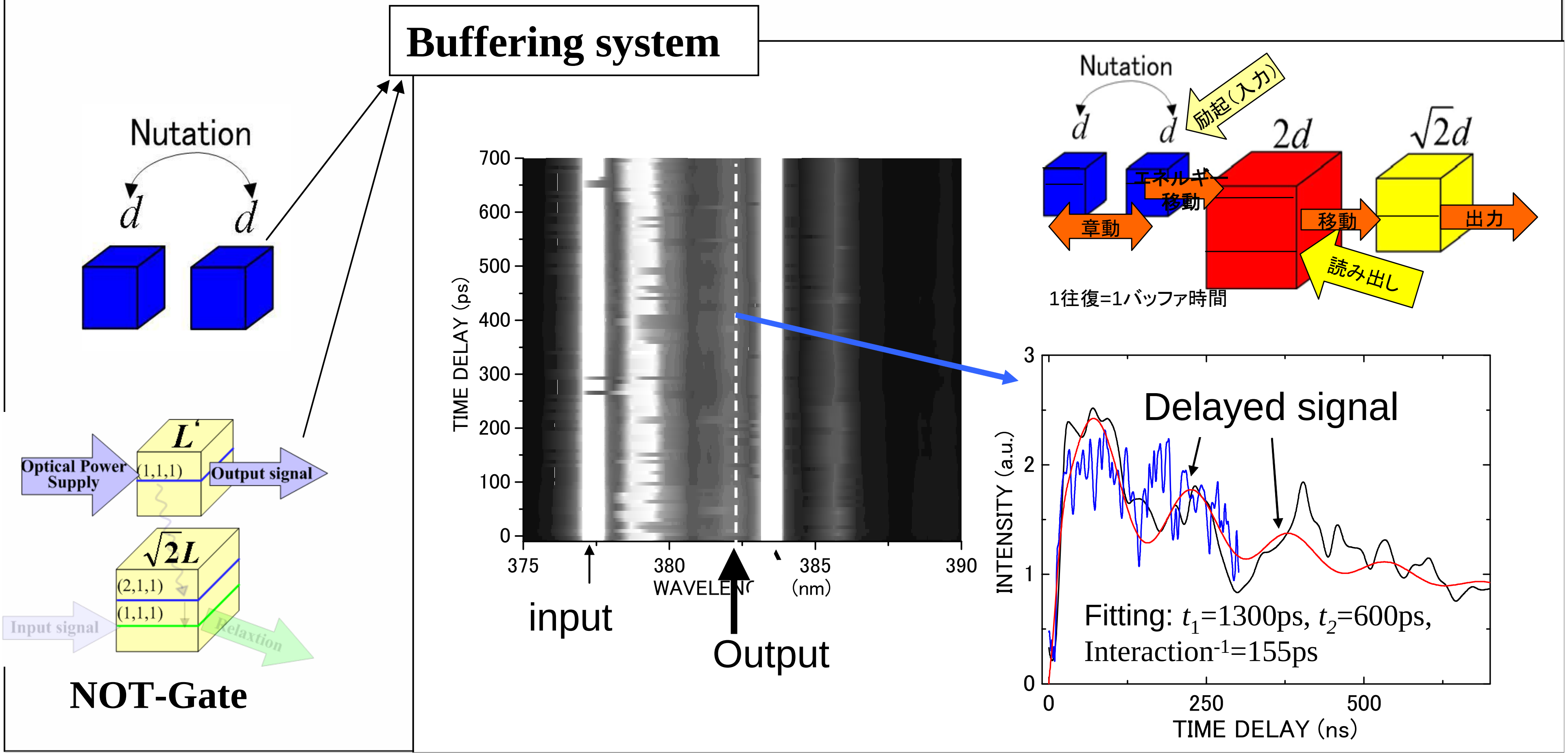


Many AND-Gates



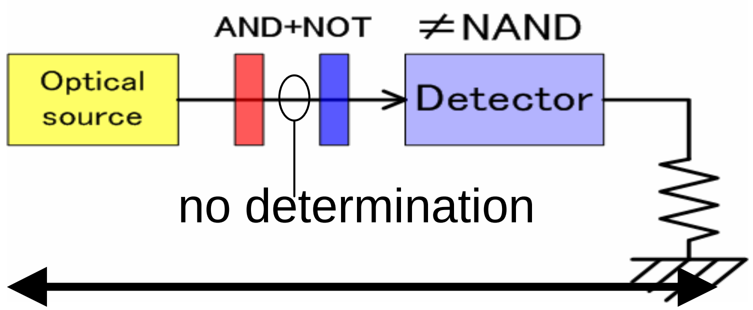
Buffering system

Combination of Nutation and NOT-gate realizes Optical Data buffering system.: CLEO/QELS 2006.



Fundamental difference: Conventional and Nanophotonic devices

Conventional photonic device



·In conventional case, device size may be decreased to diffraction limit.

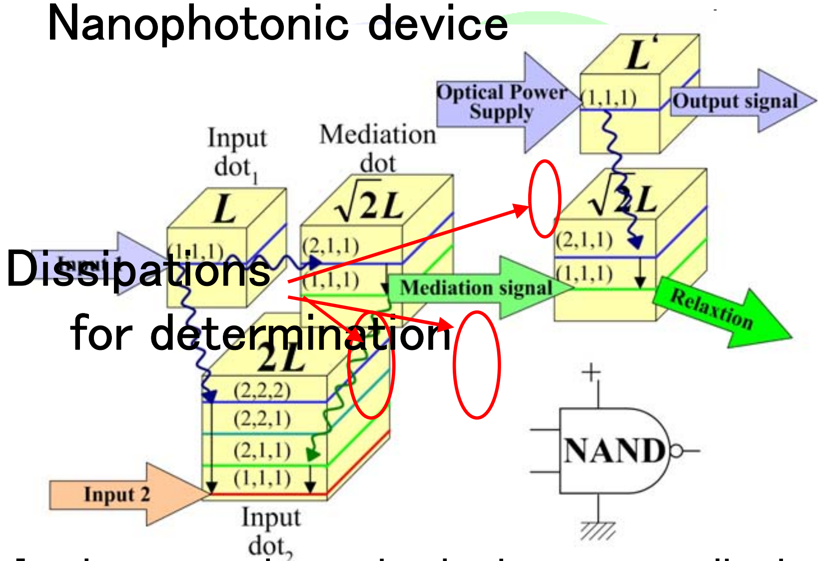
·However, operating determination is made out side of the device.->device size is large.

·Cascadability has also problem, because there is no determination in inter-device.

·When we connects AND gate and NOT gate, they could not act as NAND gate.

·So for NAND operation, we must design it as another total system as NAND-gate.

Nanophotonic device



·In the nanophotonic device, many dissipation parts for determination are in the device. ->Total device size is small.

·When we make NAND gate, we only connect AND gate and NOT gate. Because the small dissipation supports each device operation.

·This small dissipation also supports low power consumption.

Performance comparison

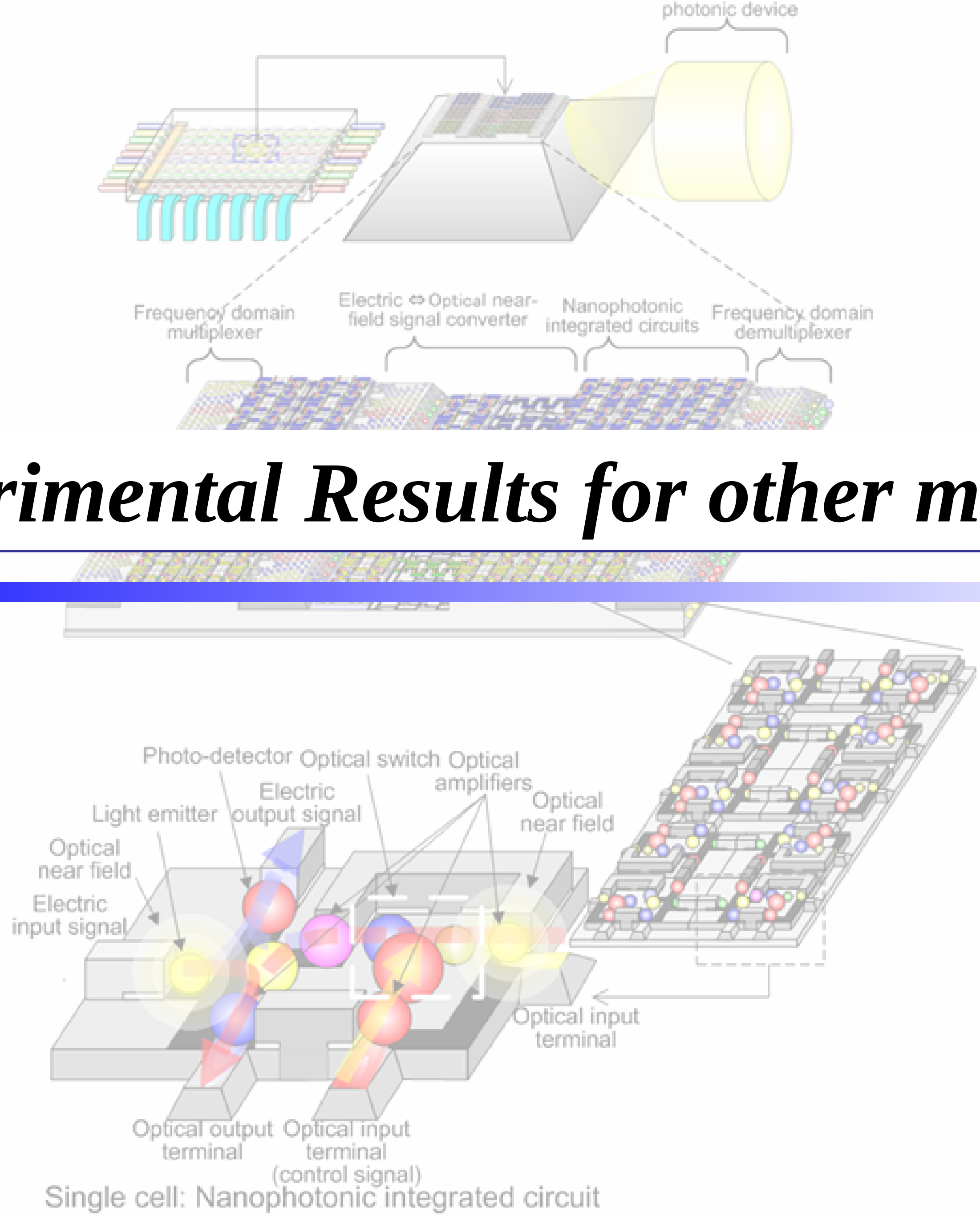
Classification	Size:V	Switching time:t_{sw}	Switching Energy:E (/cycle)	ON-OFF Contrast: C	Figure of Merit: $\frac{C}{V \cdot t_{sw} \cdot E}$
Optical MEMS	$(n\lambda)^3$	1μs	$10^{-18\sim-17}$J	10^4	$10^{-5\sim-6}$
Mach-Zehnder	$(n\lambda)^3$	10ps	$10^{-18\sim-17}$J	10^2	$10^{-2\sim-3}$
$\chi^{(3)}$ non-resonant	$(n\lambda)^3$	10fs	10^6 photons	10^3	10^{-3}
$\chi^{(3)}$ resonant	$(n\lambda)^3$	1ns	$10^{3\sim4}$ photons	10^4	$10^{-4\sim-5}$
Quantum well sub-level	$(n\lambda)^3$	100fs	$10^{3\sim4}$ photons	10^3	$10^{-1\sim-2}$
Nanophotonic switch	$(\lambda/10)^3$	～100ps	1photon	10	1～

Consideration of thermal problem

Existent electronic device (CPU) 10^9 transistors 1GHz/100W=1transistor:10^{-7}W
Nanophotonic switch 1GHz/ 1switch: 10meV × 10^9/s=10MeV/s=10^{-12}W

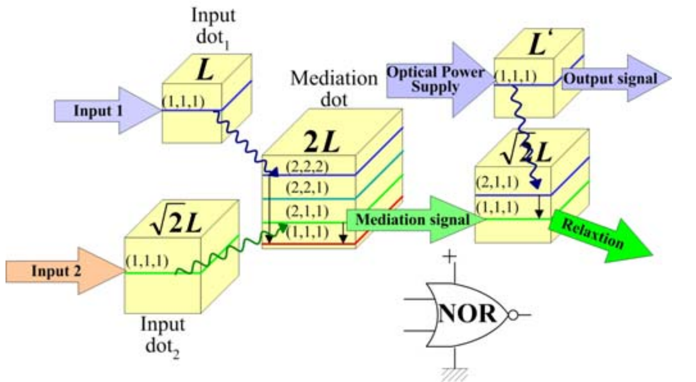
Nanophotonic switch can be integrated 10^5 times higher density than the existent electronic device (CPU).

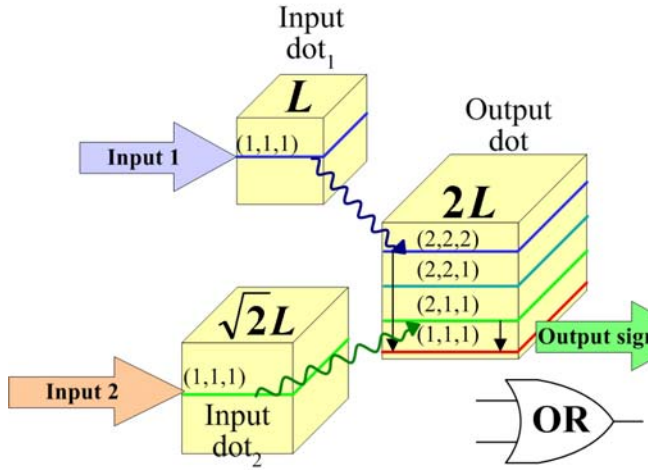
Experimental Results for other materials

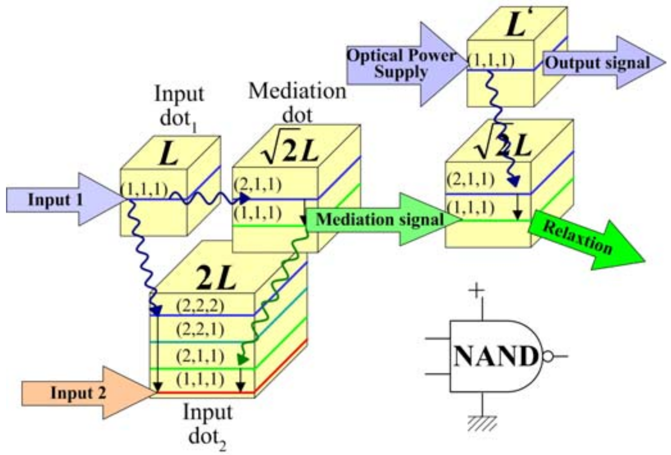


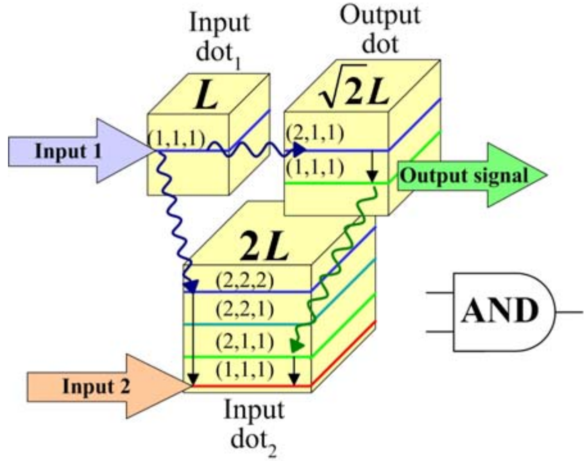
Other Logic circuits

Logic circuits

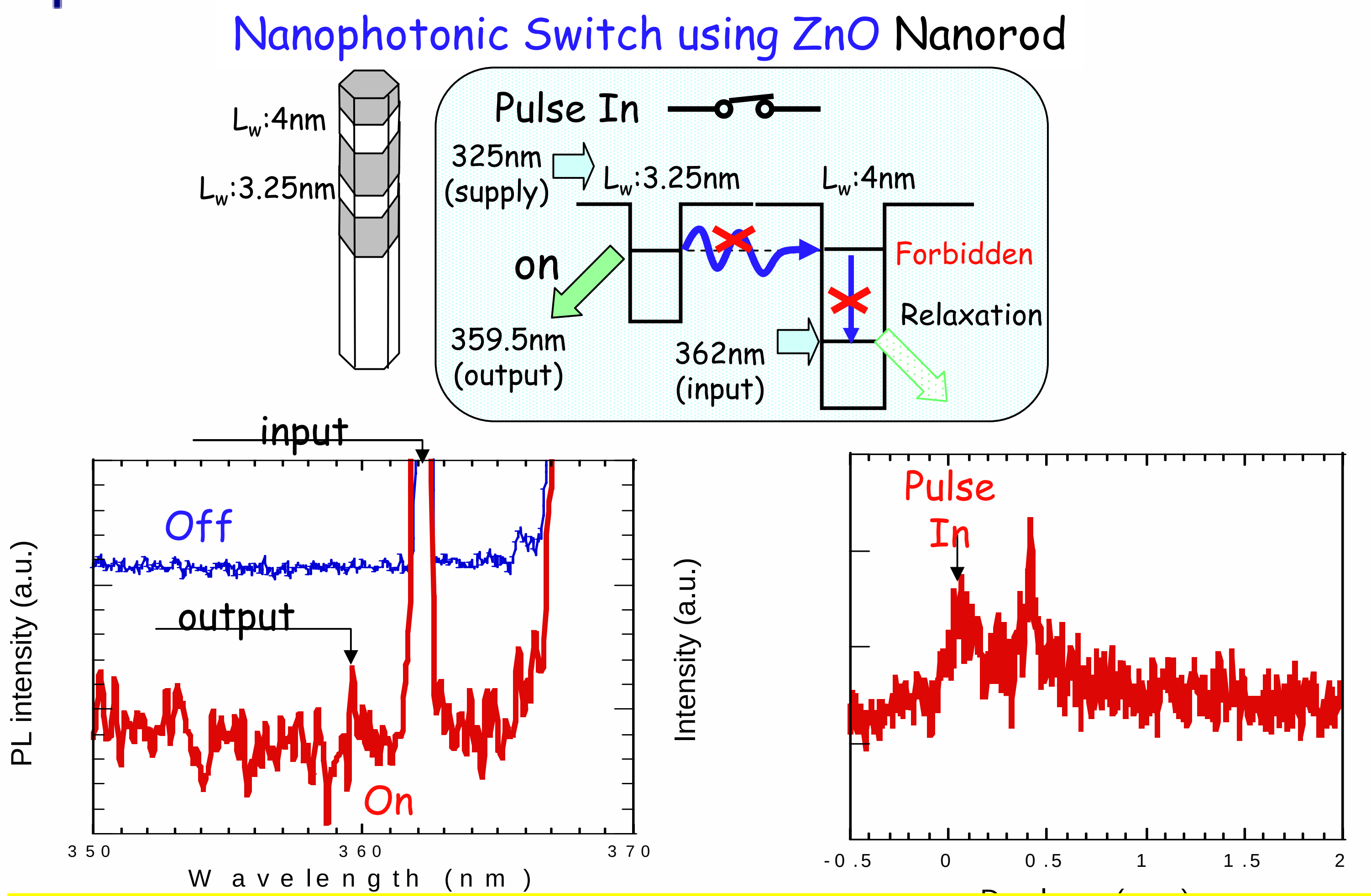








Nanophotonic Switch using ZnO Nano-rod



T. Yatsui, S. Sangu, T. Kawazoe, and M. Ohtsu, Appl. Phys. Lett., vol.90, no.22, pp.223110-1 -3, May 2007.

Nonadiabatic Photolithography

Nonadiabatic photolithography is one of the most promising method to fabricate the nanophotonic devices.

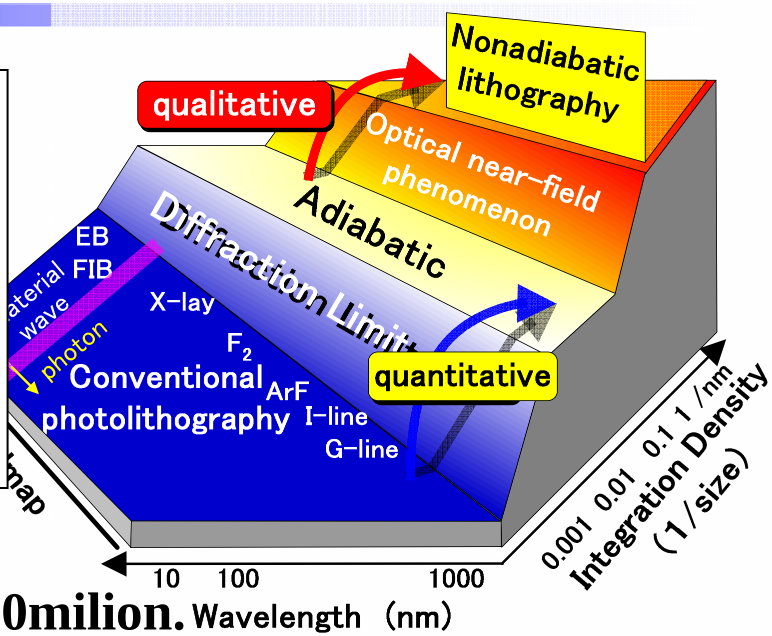
Here, I introduce the experimental results briefly.

Theory: see T. Kawazoe, et al., J. Chem. Phys.122 024715 (2005).

Background & Motivation

•Photolithography is the practical high-throughput method to produce electronic and photonic devices

•In order to make patterns much smaller, the wavelength of a light source must be shorten, due to the diffraction limit



Too expensive!!

Cost of equipment is $100milion.

Power consumption is 100billion KWh/year in Japan 2005.

We found the Nonadiabatic Photochemical Reaction.

And proposed the photolithography using the nonadiabatic reaction. (Nonadiabatic photolithography)

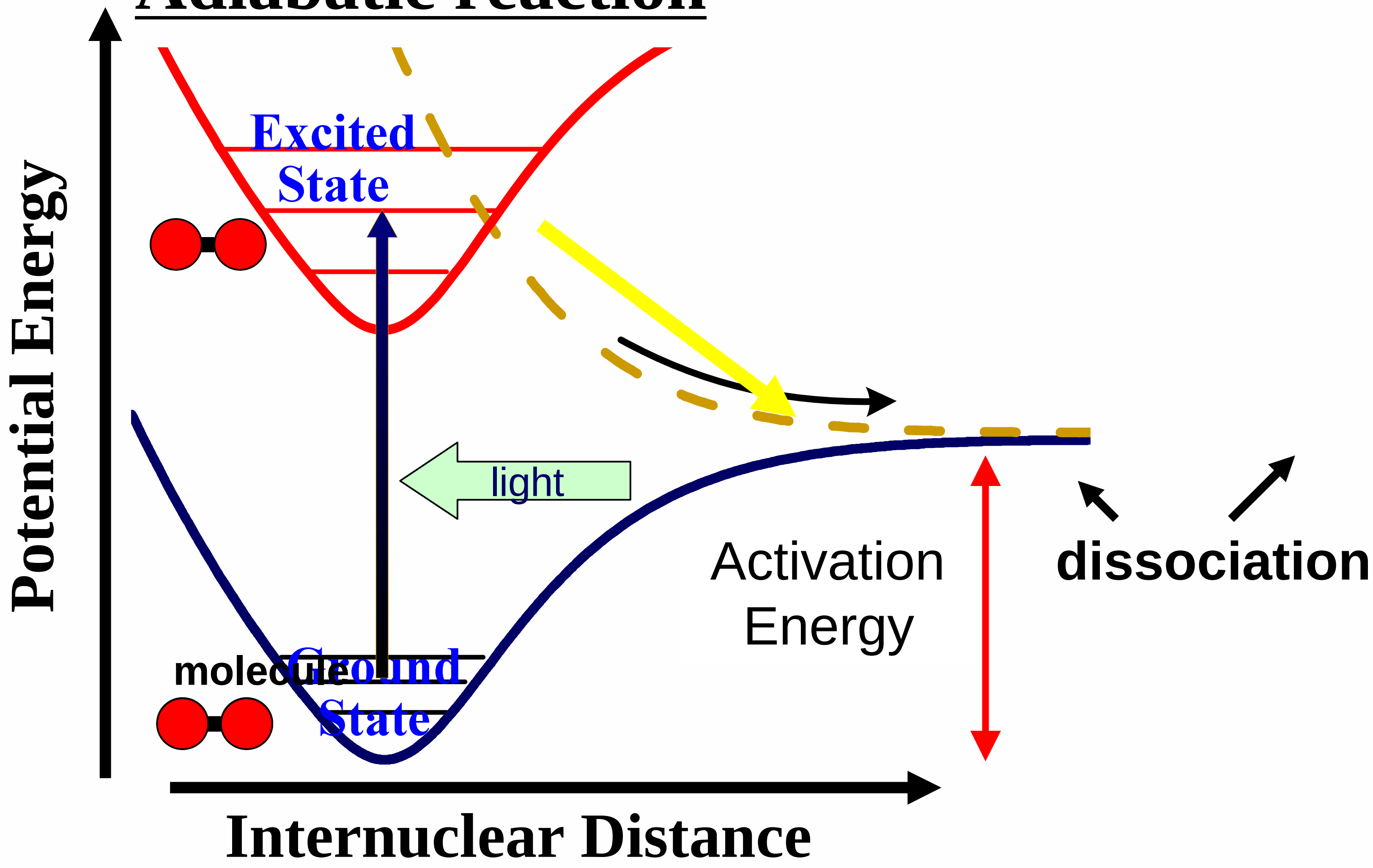
Low price of equipments

High resolution

Low power consumption

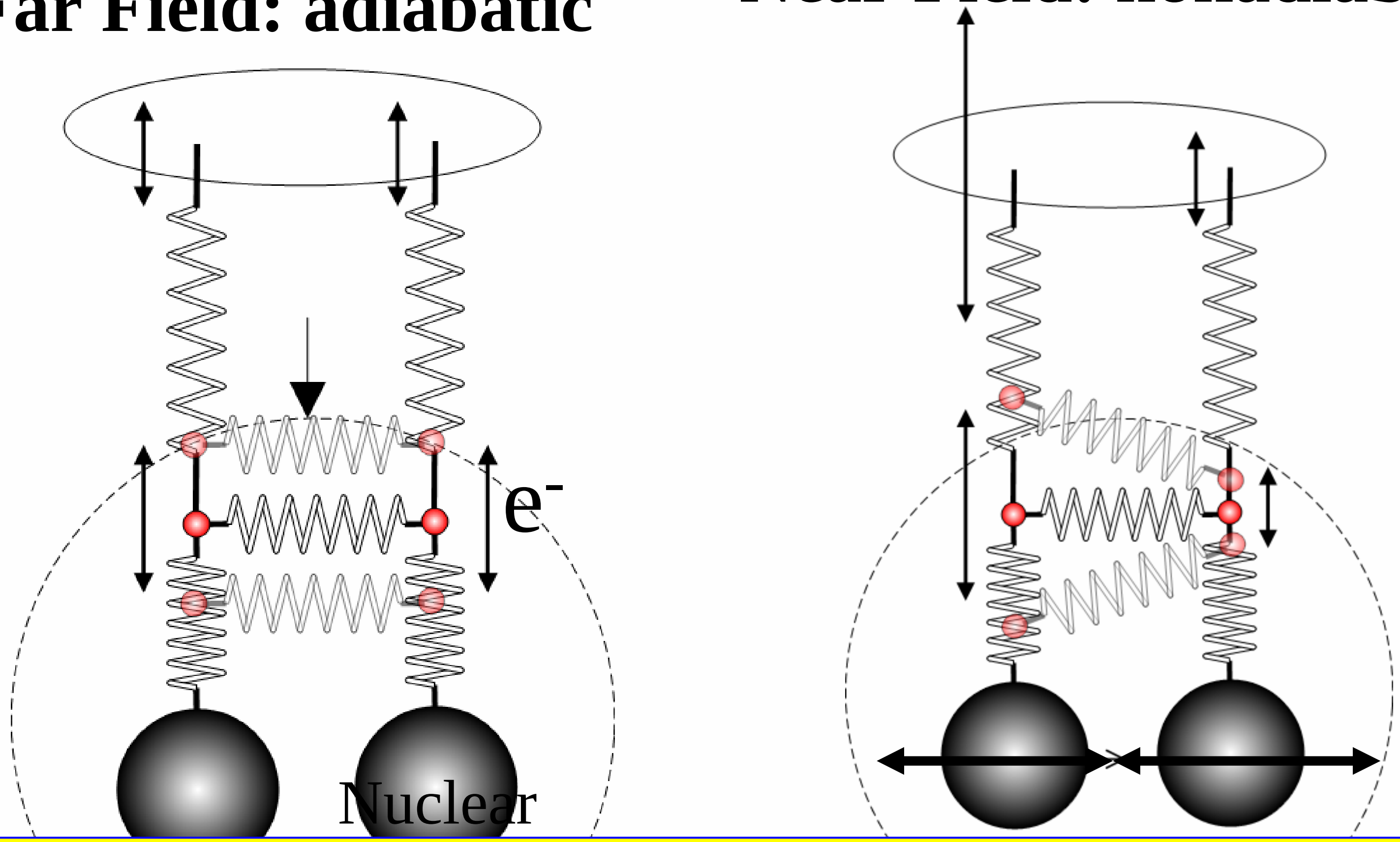
Potential Curves of Electron in Molecular Orbital

Adiabatic reaction



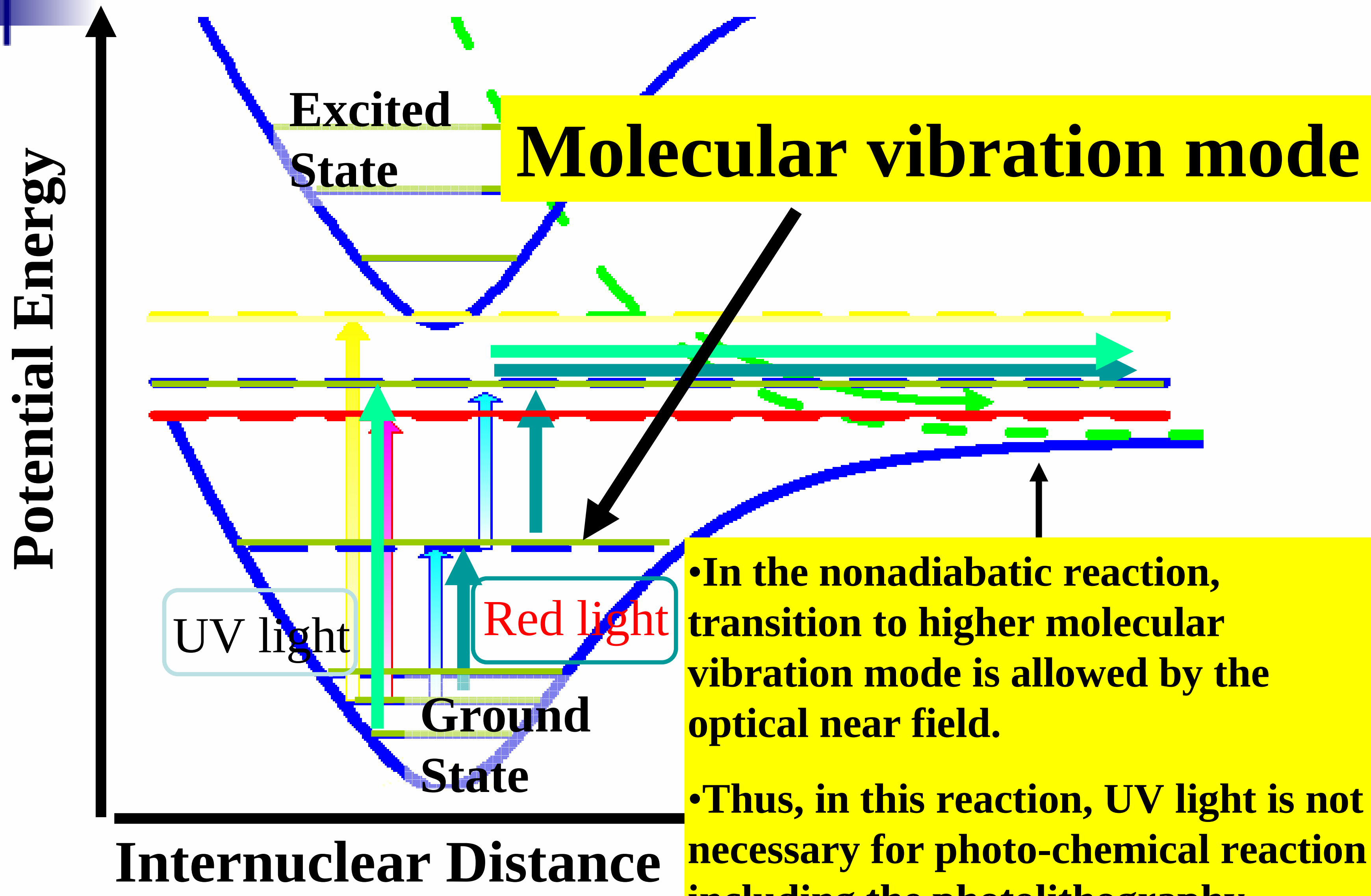
Nonadiabatic photochemical reaction

Far Field: adiabatic | **Near Field: nonadiabatic**



Steeply spatial gradient of optical near field can excite the molecular vibration mode directly.

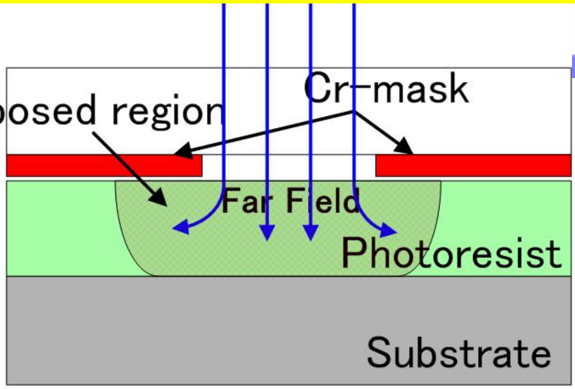
Nonadiabatic photochemical reaction

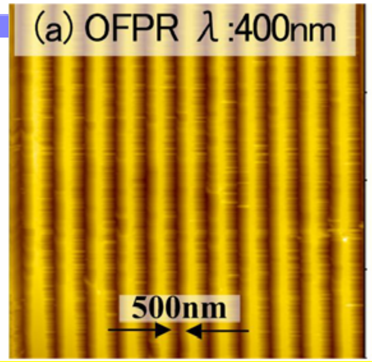


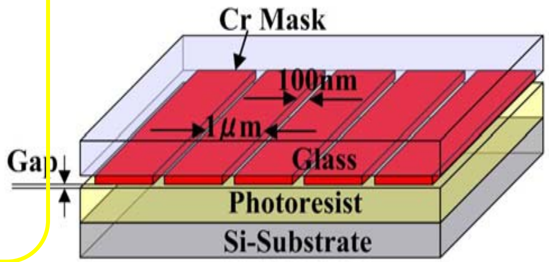
- In the nonadiabatic reaction, transition to higher molecular vibration mode is allowed by the optical near field.
- Thus, in this reaction, UV light is not necessary for photo-chemical reaction including the photolithography.

Comparison of typical fabricated results

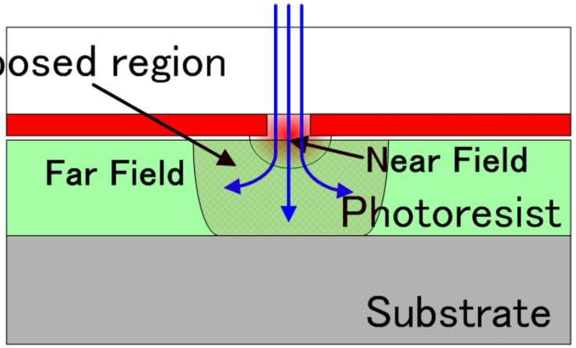
Contact exposure

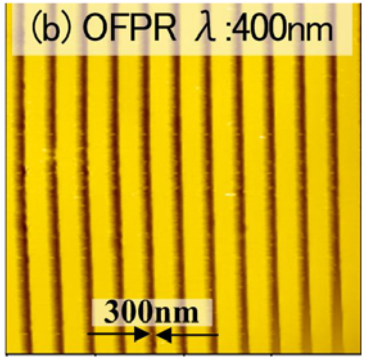




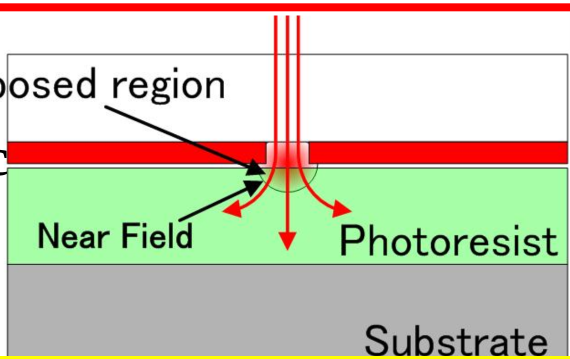


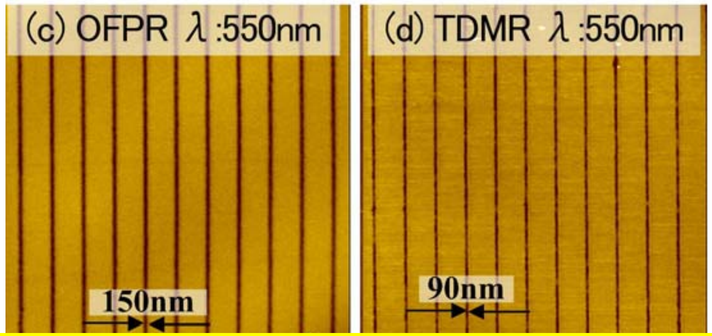
Near-field exposure





Nonadiabatic exposure

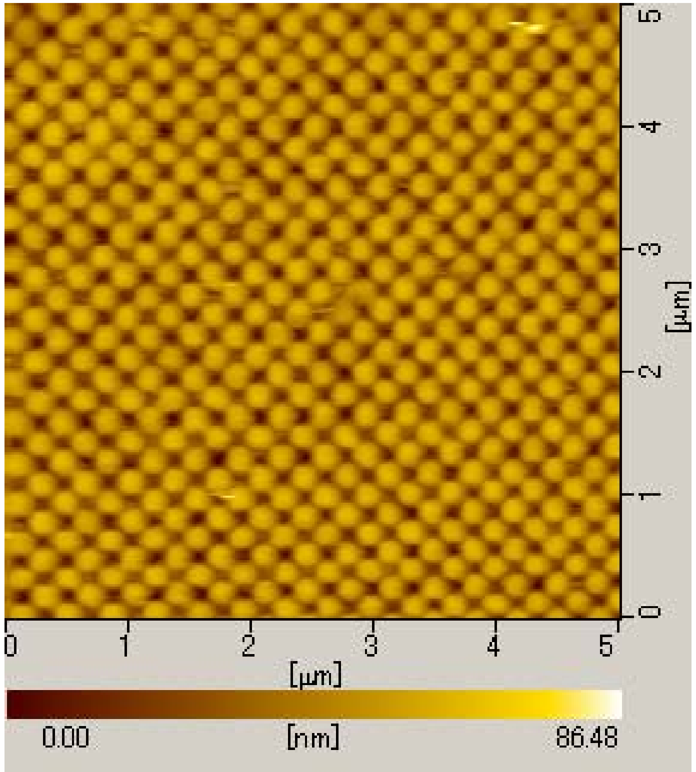




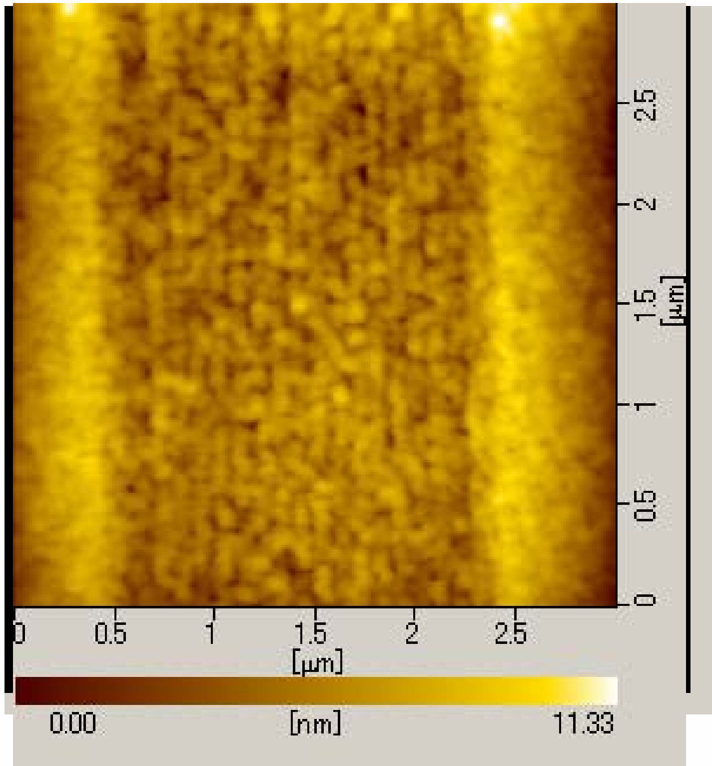
H. Yonemitsu, T. Kawazoe, et. al, J. Lumin. 122-123, PP.230-233 (2007).

Application Nonadiabatic Reaction to Photolithography II

This method increase in the resolution of photolithography.
By using 550 nm light,
Fabrication of 45nm-L&S was succeeded.



HP125nm: 2-dimentional array



HP45nm: L&S

Prototype stepper by Canon Co. LTD. & Univ. Tokyo

Prototype stepper was completed (2006).
It has 32nm resolution, but its cost was less than 10% of EUV stepper and EB lithography.