Simulation of Photodetection using FDTD Method with Application to Near-Field Subwavelength Imaging Based on Nanoscale Semiconductor Photodetector Array

Ki Young Kim, Yingyan Huang, Boyang Liu, and Seng-Tiong Ho

Department of Electrical Engineering and Computer Science
Northwestern University, Evanston, IL 60201

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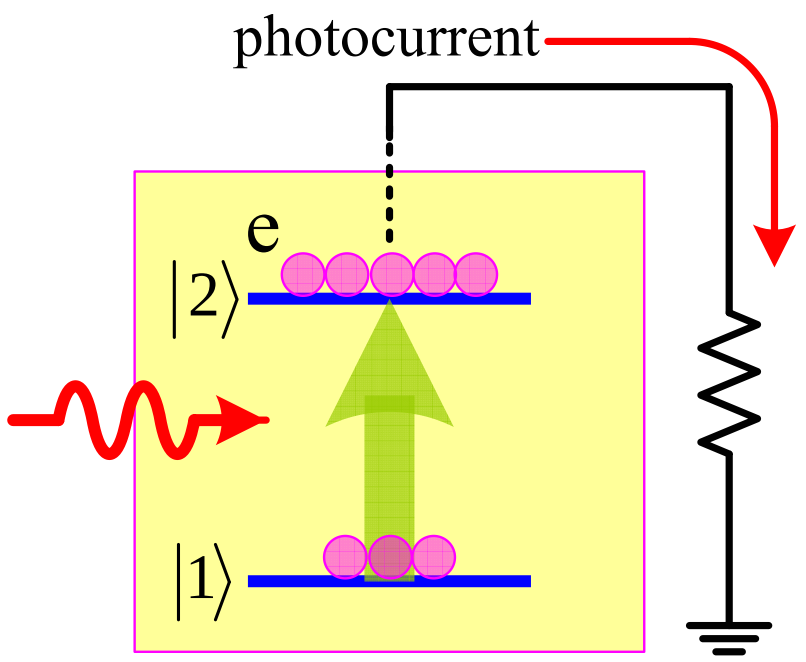
Introduction

- **Photon → Current: Photodetector**
- Photocurrent generated in semiconductor material from incident light is one of core parameters characterizing performance of a photodetector.
- Conceptually, a photodetector can be simply modeled as a medium with two energy levels.
- The photocurrent generated in the semiconductor is dependent on the incident (excitation) wavelength and the energy band gap structure of the semiconductor material.



- **Photocurent** can be derived from EMPTYING the electrons in the upper level through an external electric circuit.

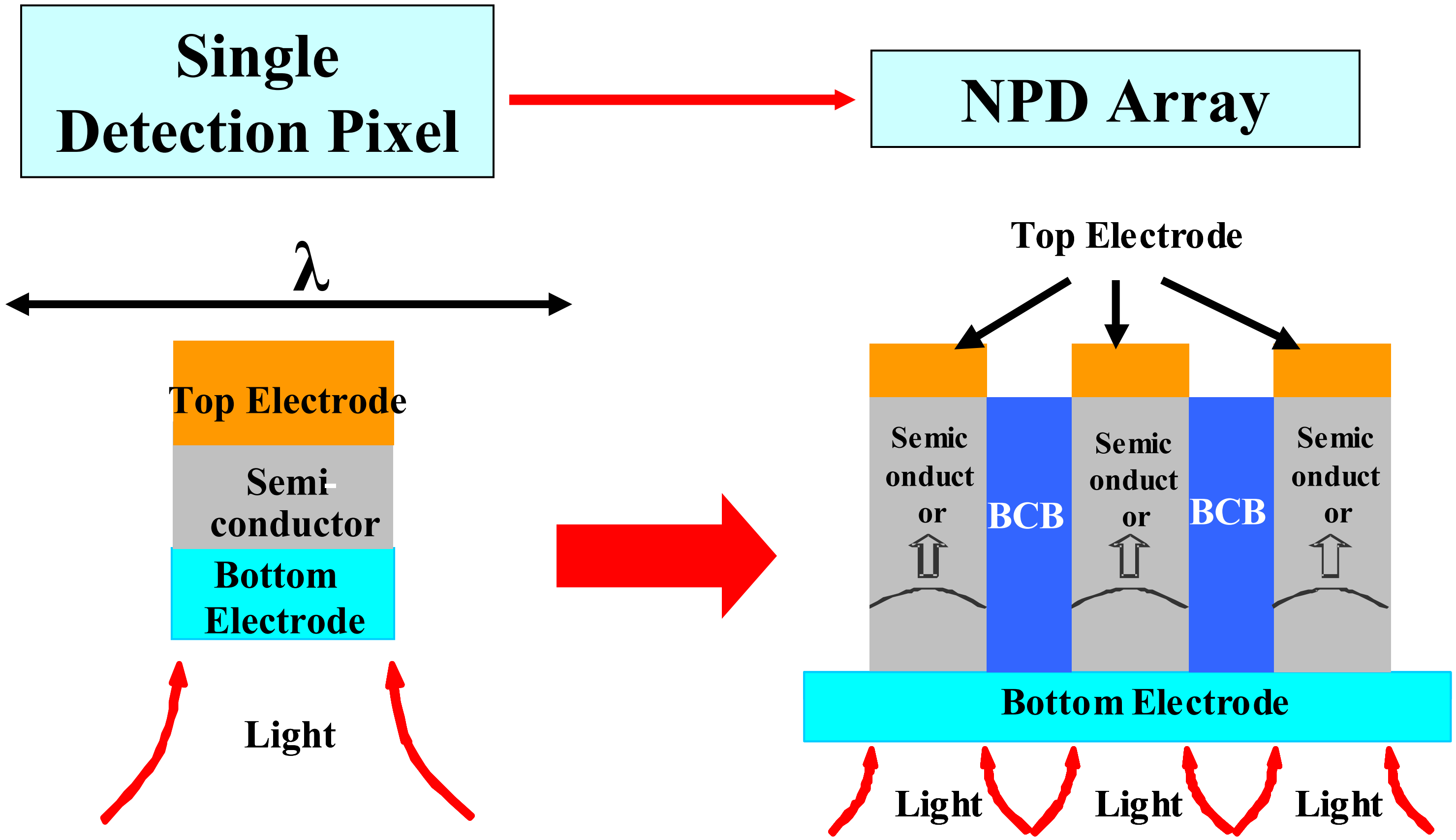
- **Simulation method** that can investigate both the **light propagation** and the **physical mechanisms of the photodetection via semiconductor materials** will be quite useful in terms of predicting various performances of optoelectronic devices using semiconductors.

- We are reporting a method to simulate photodetection in semiconductor material using finite-difference time-domain (FDTD) method.

- Its application to simulating near-field subwavelength imaging based on nanoscale photodetector (NPD) array.

NPD ARRAY

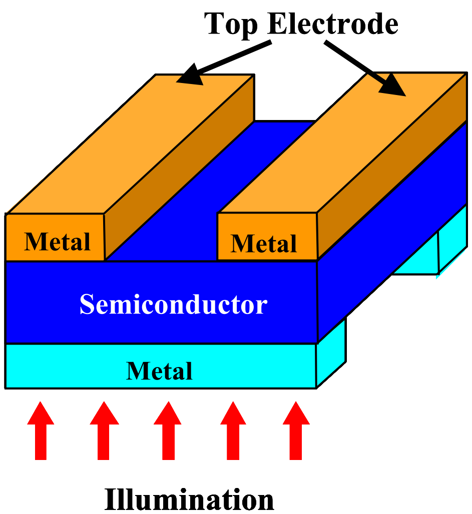
Basic structures of Nanophotodetector (NPD) Devices:



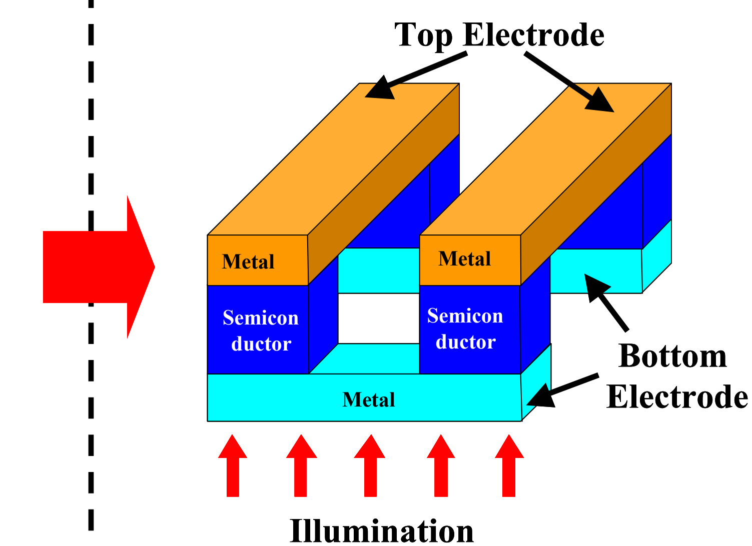
II. DEVICE DESIGN FOR NPD ARRAY

- **Addressing function:**
  - **Top and bottom electrode perpendicular to each other, enabling addressing**
  - **M + N electrode stripes ➔ M x N addressable pixel array**

Slab Version



Channelized Version

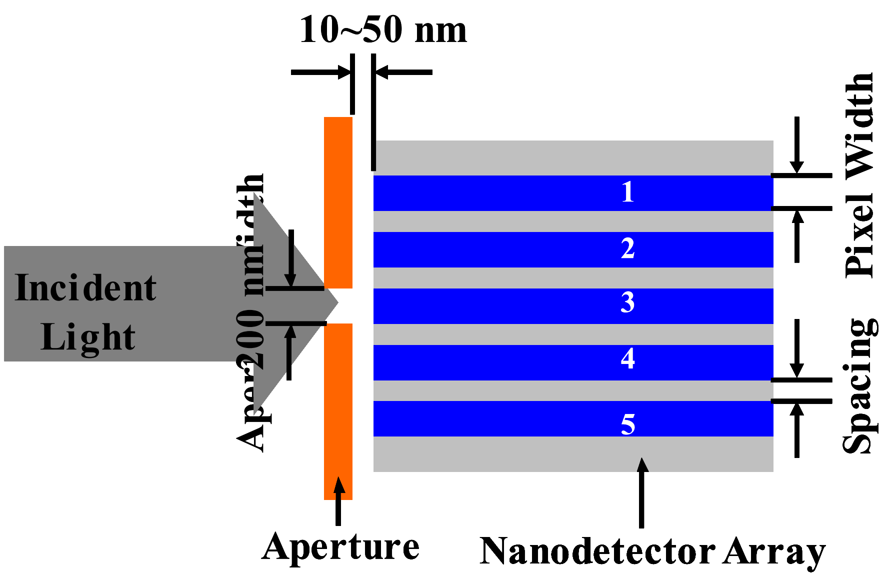


Top view (4 x 4 array)

Top view of channelized NPD Array

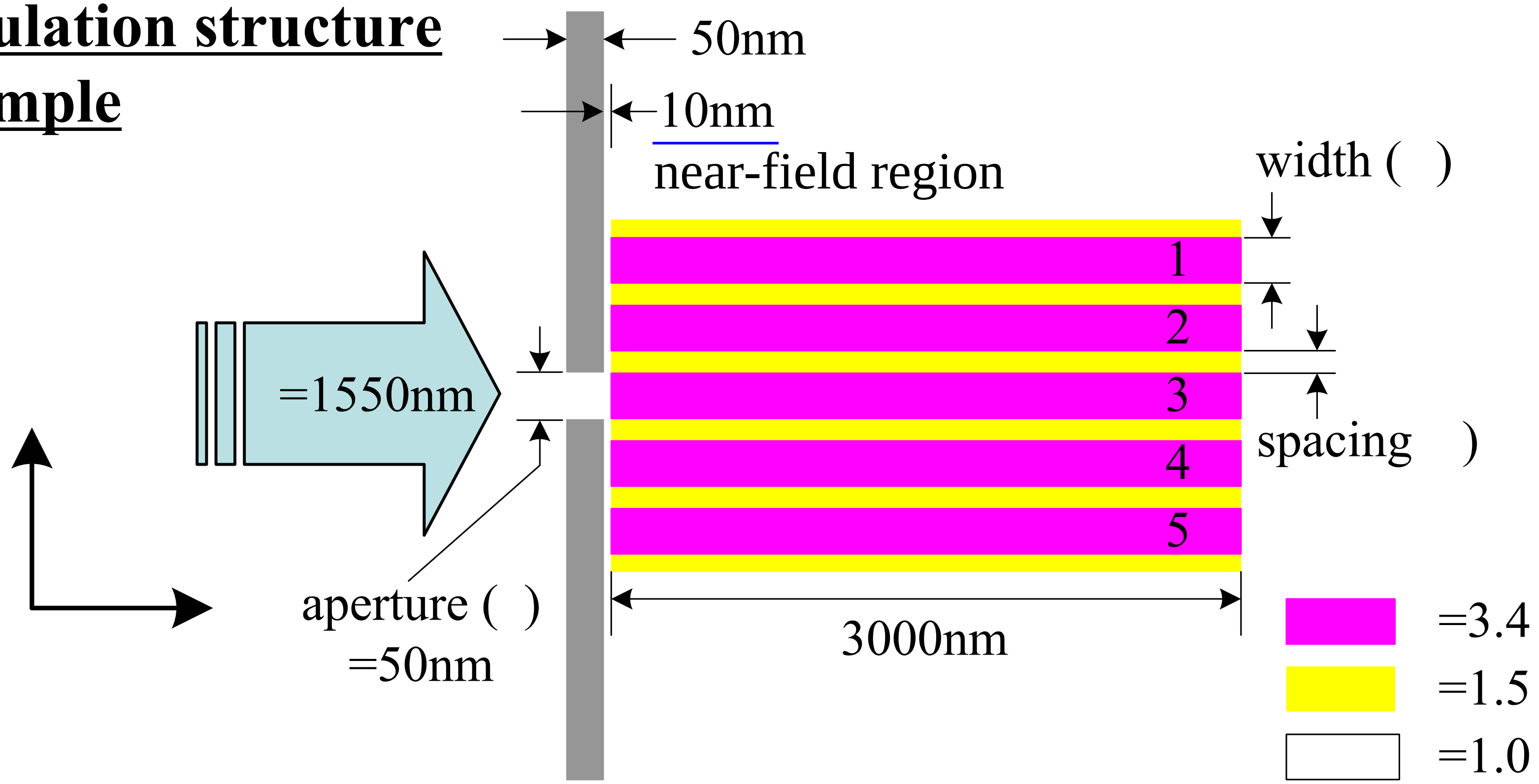
Simulation of Photodetection using FDTD method

- **Simulation structure for NPD array**
  - **Single slit simulates tiny object**
  - **Distance between aperture and NPD array is in the near-field region**
  - **Refractive index : 3.46 (for pixel), 1.5 (for filling material between pixels)**
  - **High index pixel could guide the wave, increasing resolution (single mode WG~ λ /2(n) ~ λ /7)**



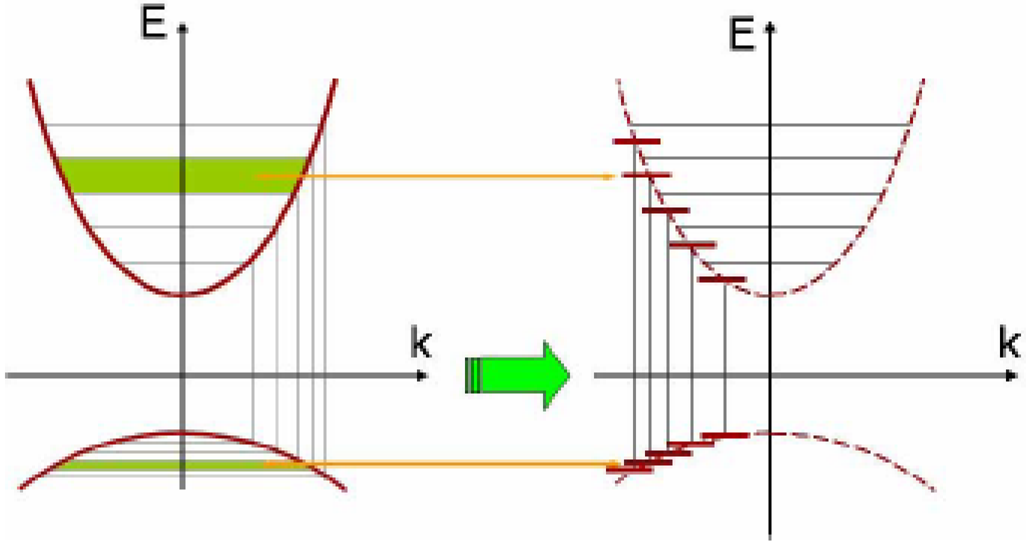
Simulation of Photodetection using FDTD method

Simulation structure Example



- NPD: semiconductor (*n*=3.4) array with filling dielectric (*n*=1.5)
- 5 fingers of NPD pixels
- **Center-to-center distance (ccd):** 150nm, filling factor = *w* / ccd

Multi-level multi-electron (MLME) FDTD algorithm

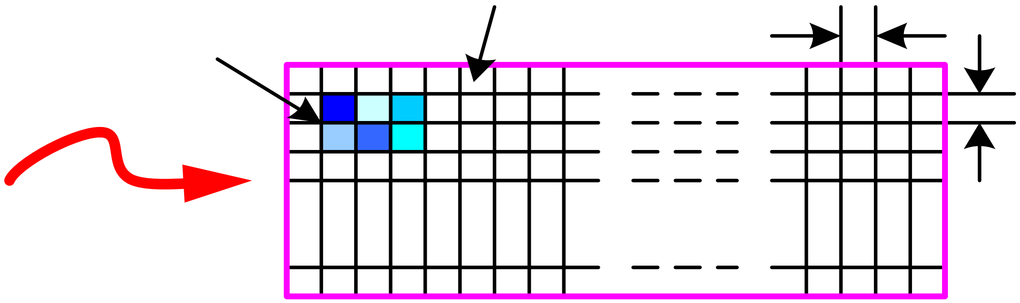


Pauli exclusion principle is incorporated into the rate equation for the semiconductor material with appropriate energy band gap enabling us to describe the medium carrier dynamics together with its absorption behavior on the light wave propagated.

Y. Huang and S. –T. Ho, "Computational model of solid-state, molecular, or atomic media for FDTD simulation based on a multi-level multi-electron system governed by Pauli exclusion and Fermi-Dirac thermalization with application to semiconductor photonics," *Optics Express* **14**, 3569-3587 (2006)

Y. Huang, *Simulation of Semiconductor Materials using FDTD method*, M. S. Thesis, Northwestern University, 2002

Photocurrent with MLME FDTD method



$$I_{ph} = \frac{q}{t_{sim}} N$$

$$= \frac{q}{t_{sim}} \left(\sum_{pixel} N_2 \right) N_{density} \cdot A \cdot H$$

q: charge (1.6×10^{-19}C)

t_{sim}: total time simulated (1.0ps)

N: total number of electrons

N_2: normalized number of electrons in the upper level

$N_{density}$: number of electrons per unit volume $\boxed{(0.563\times10^{22}/\mathrm{m}^3)}$

$A(=dx\times dy)$: area of FDTD pixel ($5\mathrm{nm}\times5\mathrm{nm}$)

H: height of the NPD (300nm)

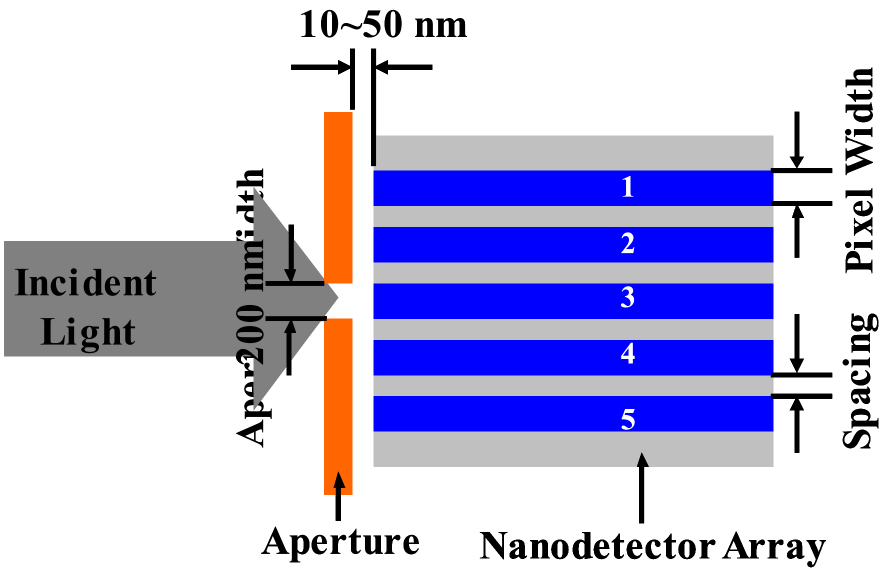
Absorption: $0.5/\mu m$

MLME FDTD SIMULATION OF NPD ARRAY

- **FDTD simulation is used to**
  - **obtain the smallest available resolution by NPD array**
  - **optimize NPD pixel width & pixel spacing for different resolution**
  - **understand the physics behind nano-imaging by NPD array**

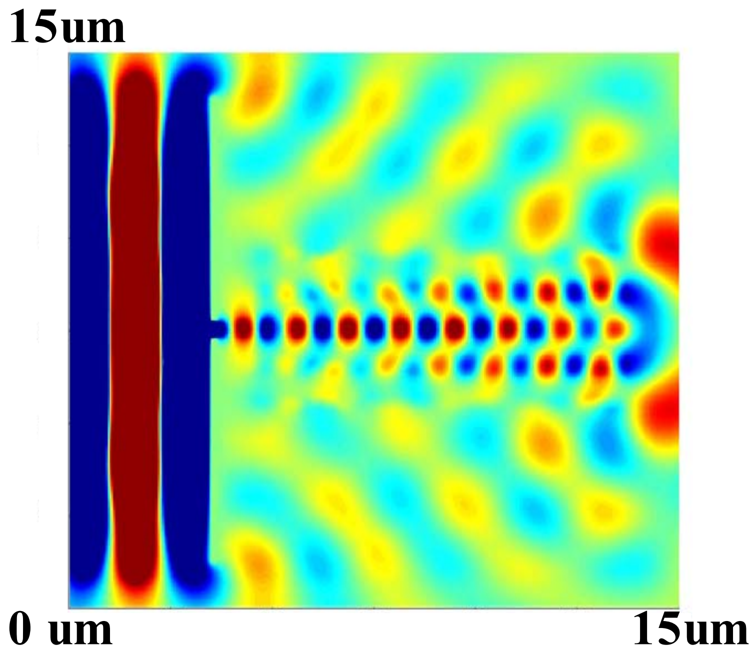
MLME FDTD SIMULATION OF NPD ARRAY

- **Simulation structure for NPD array**
  - **Single slit simulates tiny object**
  - **Distance between aperture and NPD array is in the near-field region**
  - **Refractive index : 3.46 (for pixel), 1.5 (for filling material between pixels)**
  - **High index pixel could guide the wave, increasing resolution (single mode WG~ λ /2(n) ~ λ /7)**

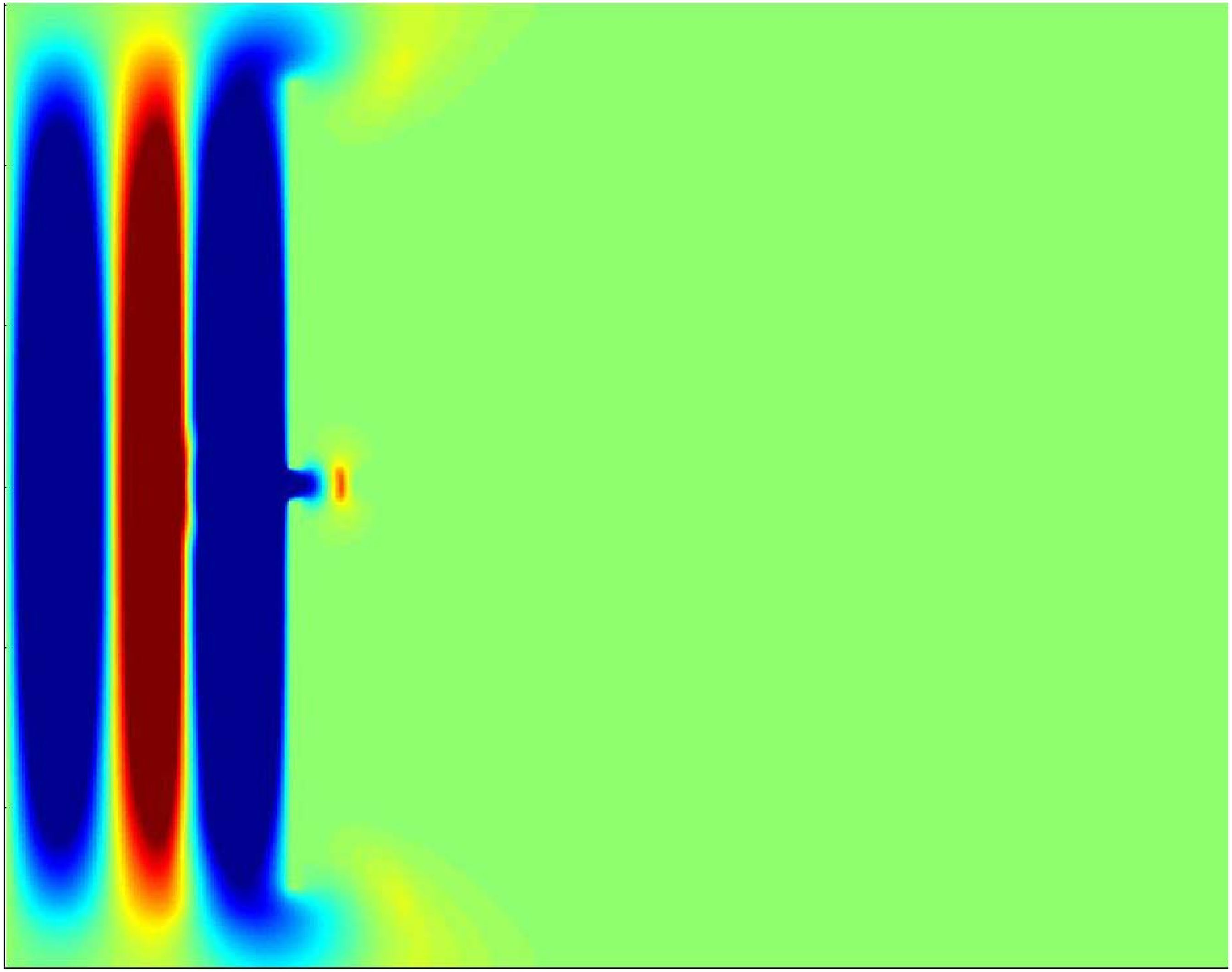


MLME FDTD SIMULATION OF NPD ARRAY

- **Optical coupling between pixels can cause cross talk between adjacent pixels**

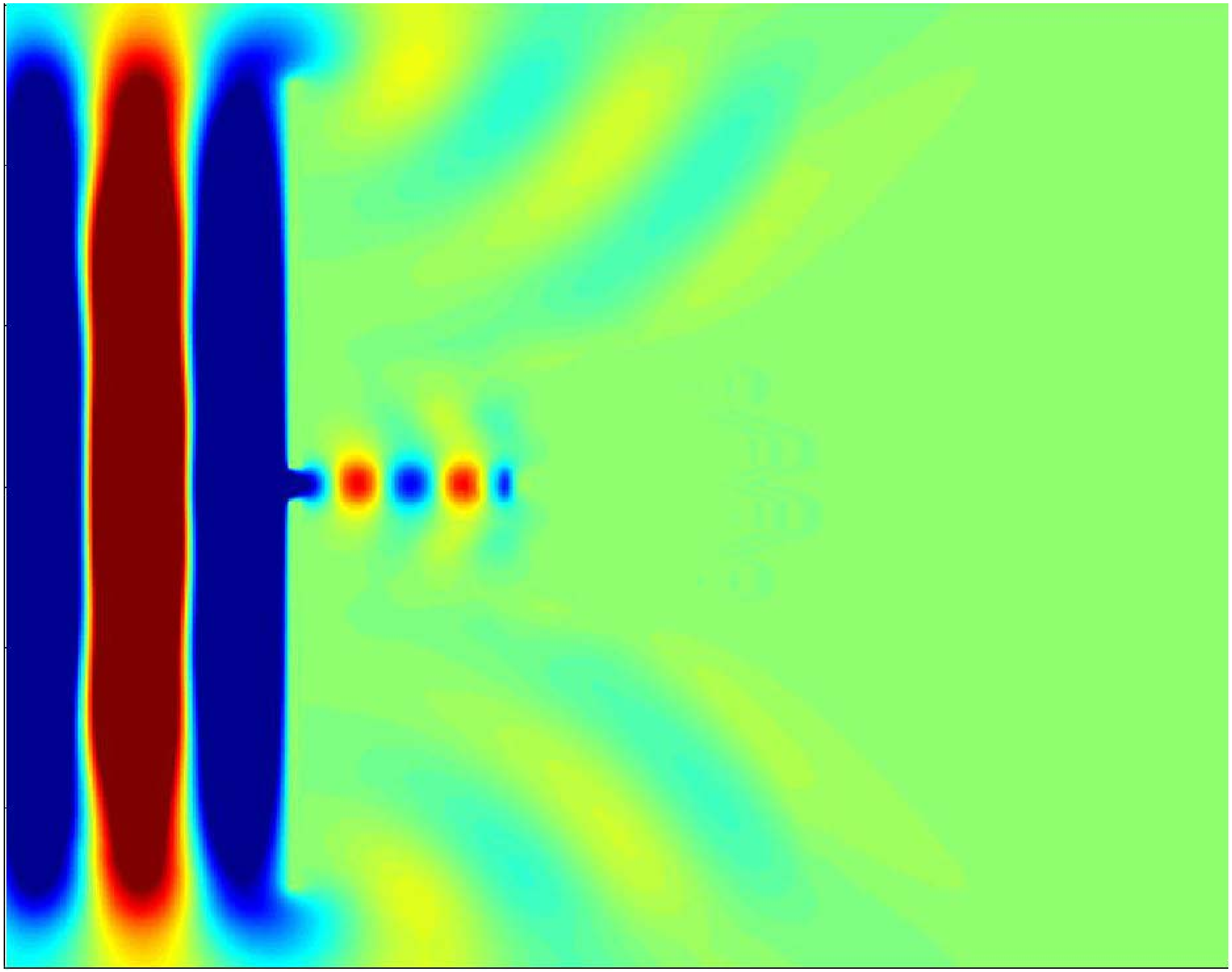


III. MLME FDTD SIMULATION OF NPD ARRAY



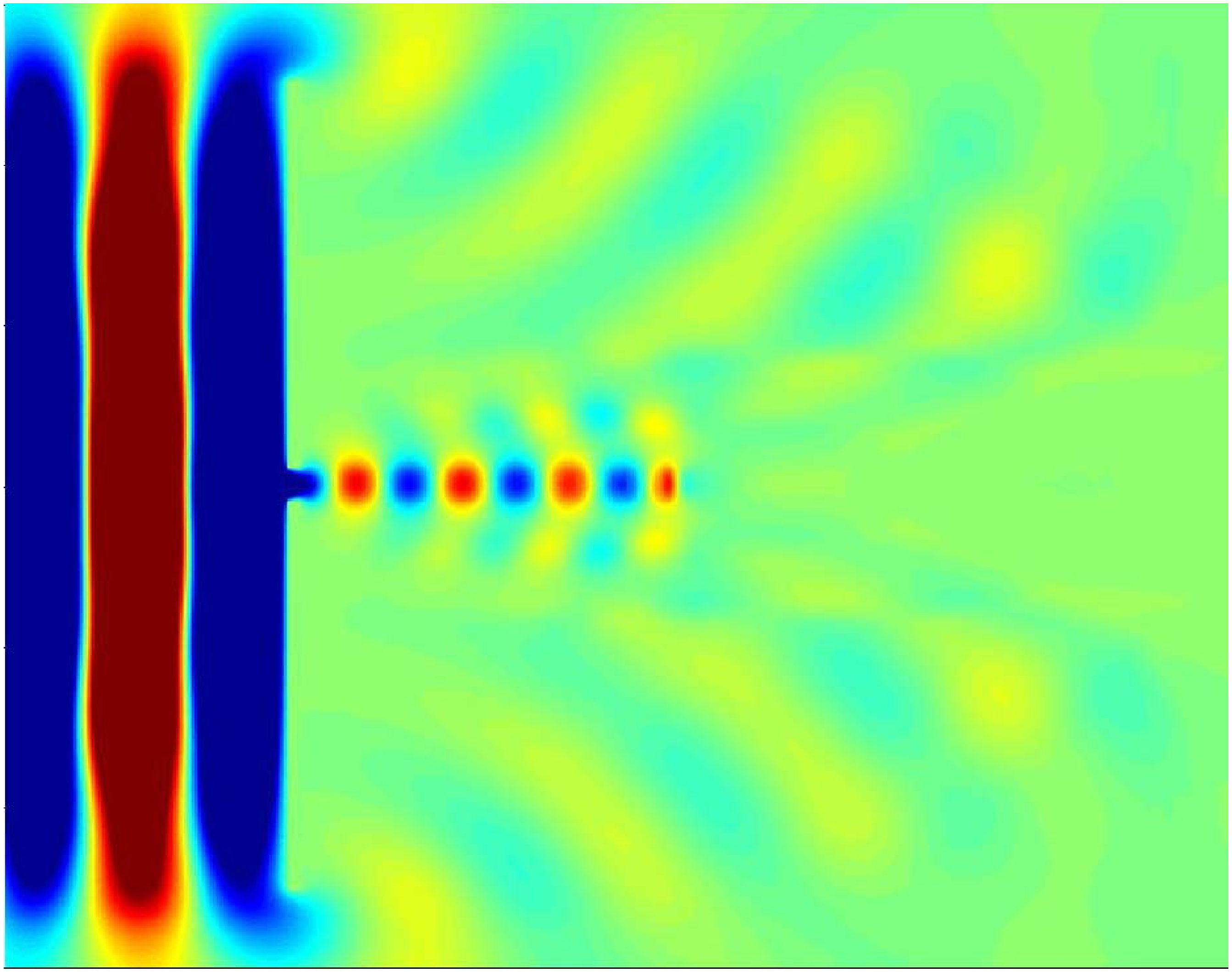
Coupling between pixels

III. MLME FDTD SIMULATION OF NPD ARRAY



Coupling between pixels

III. MLME FDTD SIMULATION OF NPD ARRAY



Coupling between pixels

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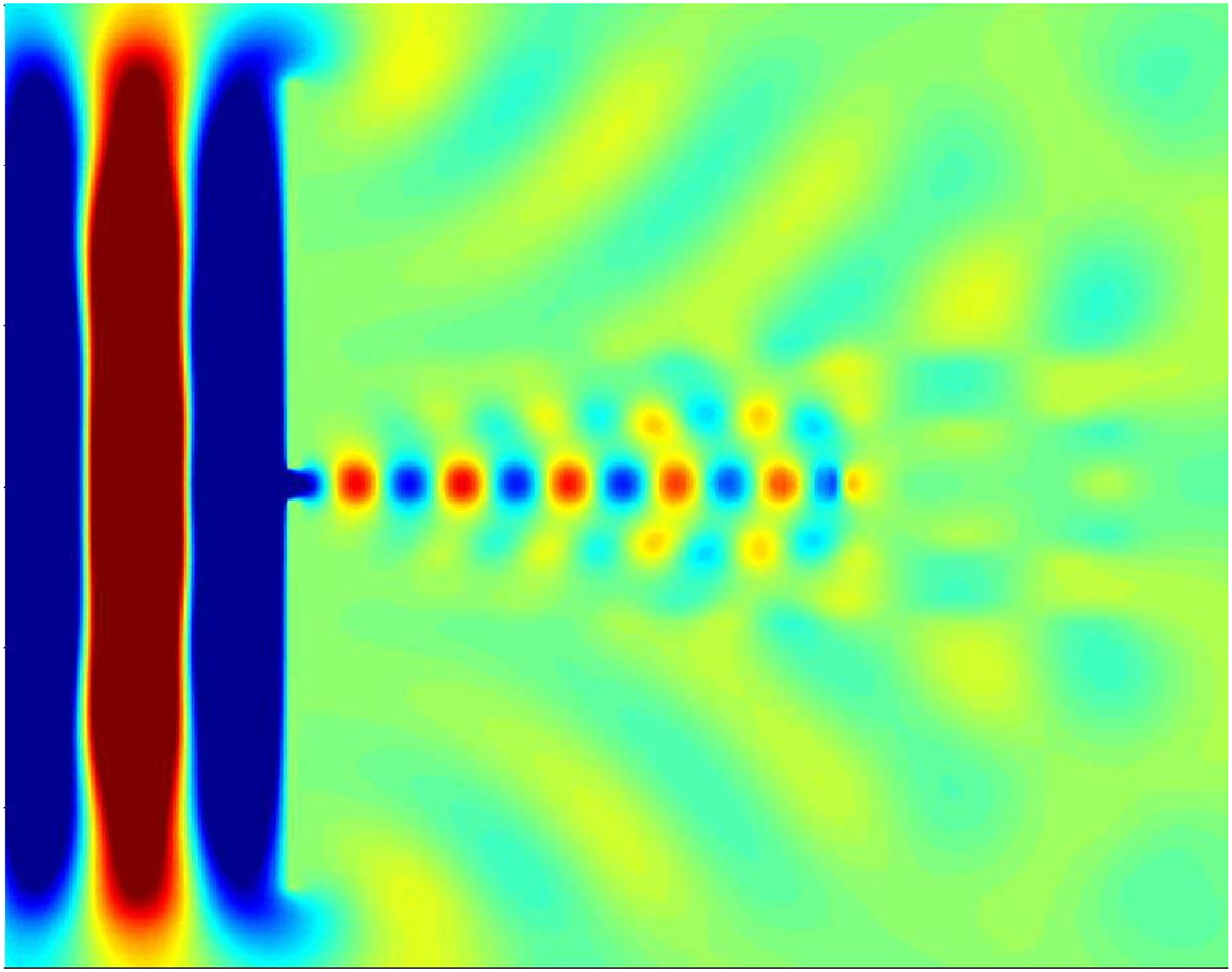

Coupling between pixels

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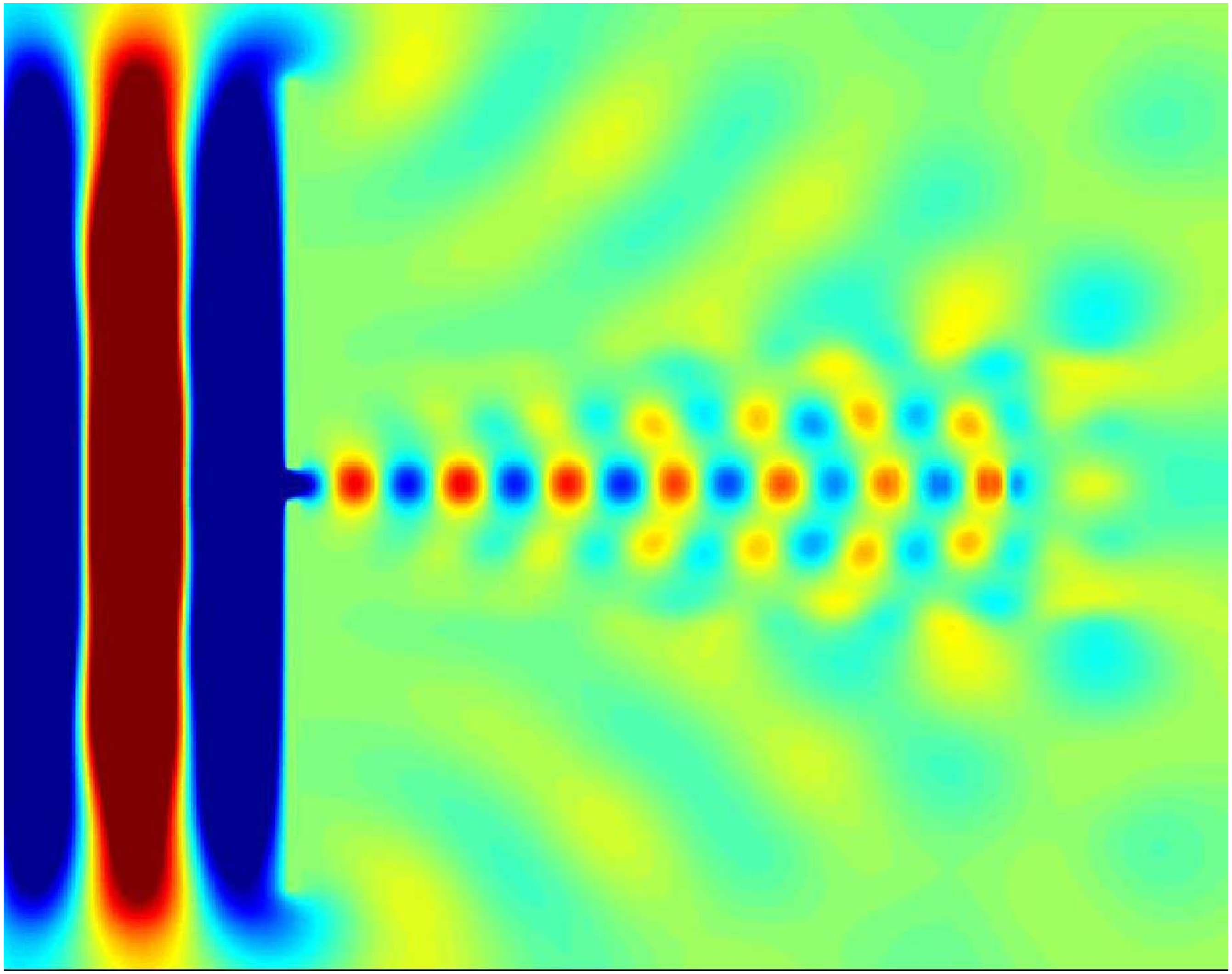

Coupling between pixels

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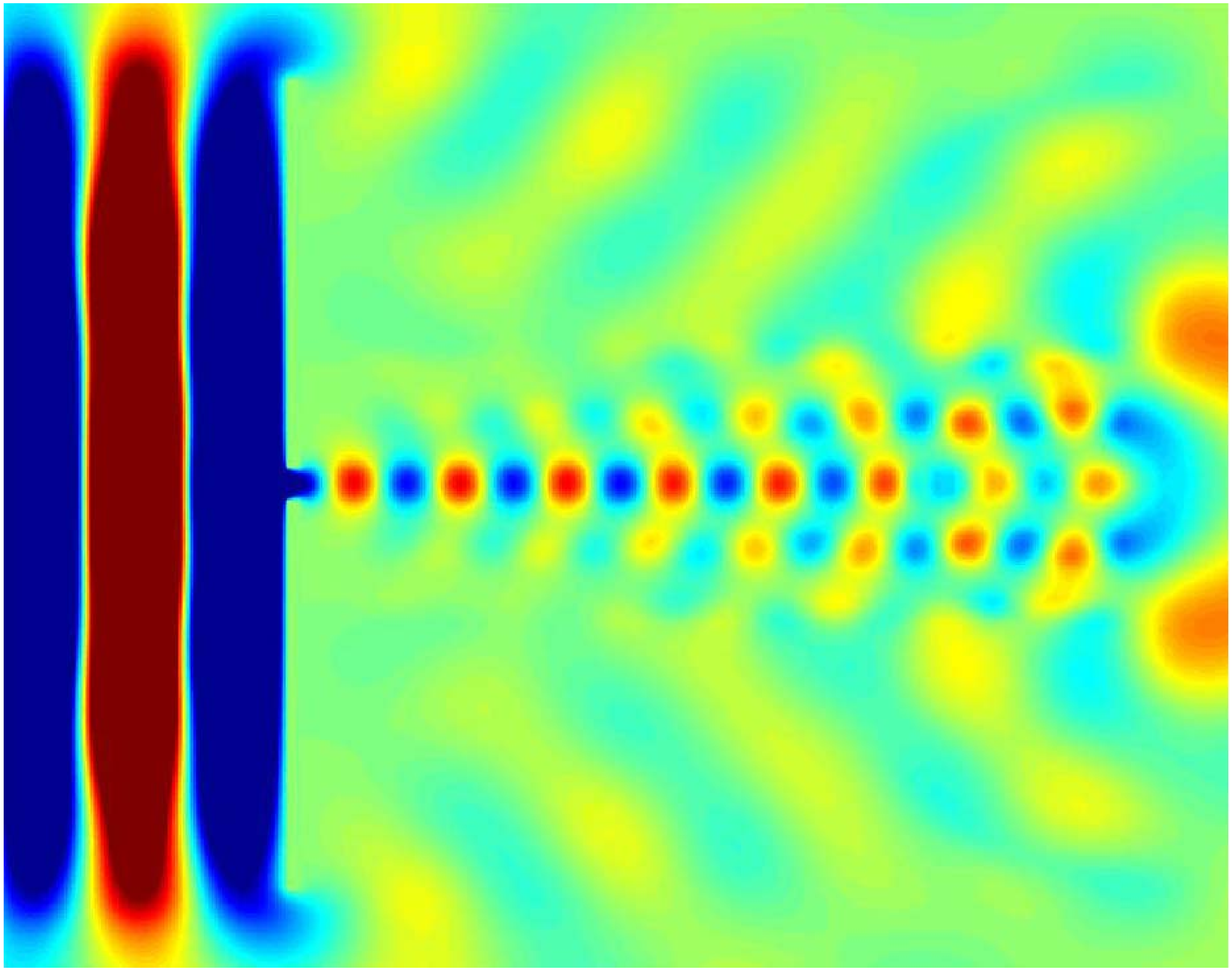


Coupling between pixels

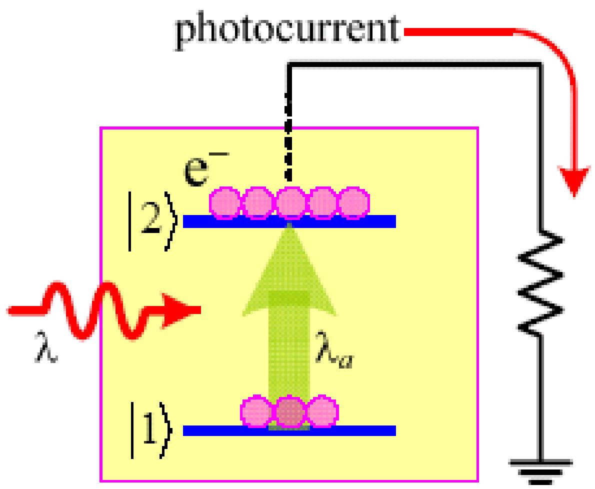
III. MLME FDTD SIMULATION OF NPD ARRAY

- **When pixel material is absorbing, optical coupling can be reduced**
- **Optical coupling can also be reduced by changing pixel width and spacing**
- **To investigate the optimal structure of NPD device more accurately, it is necessary to incorporate the active material function into FDTD simulation**

III. MLME FDTD SIMULATION OF NPD ARRAY

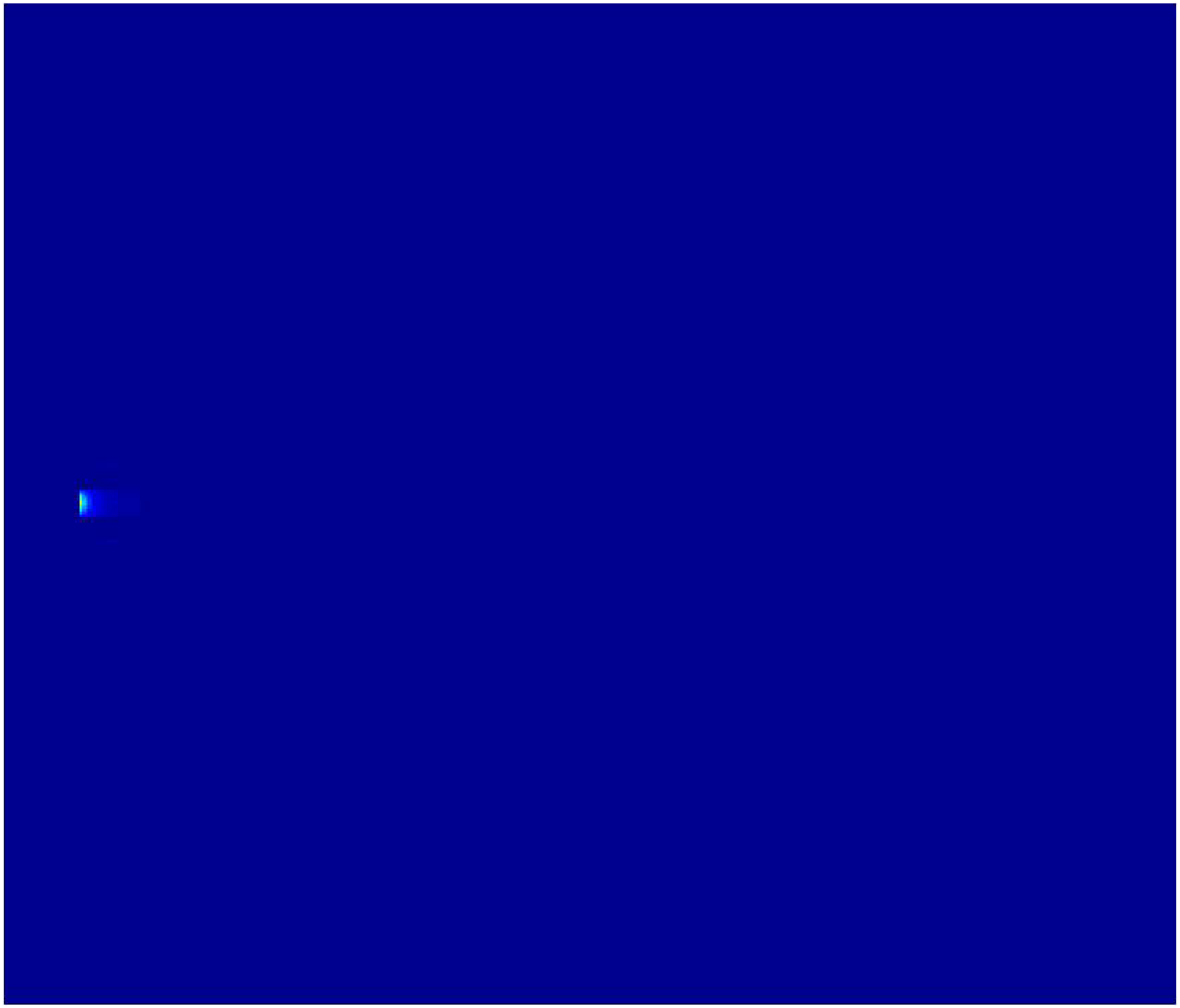
- **Multi-level multi-electron (MLME) FDTD simulation**
  - **Material absorption is considered.**
  - **Absorbing coefficient is calibrated to match real InGaAs material responses**
  - **Photocurrent could be derived from electron numbers on upper level**

Yingyan Huang and Seng-Tiong Ho, 17 April, 2006 / Vol. 14, No. 8 / OPTICS EXPRESS



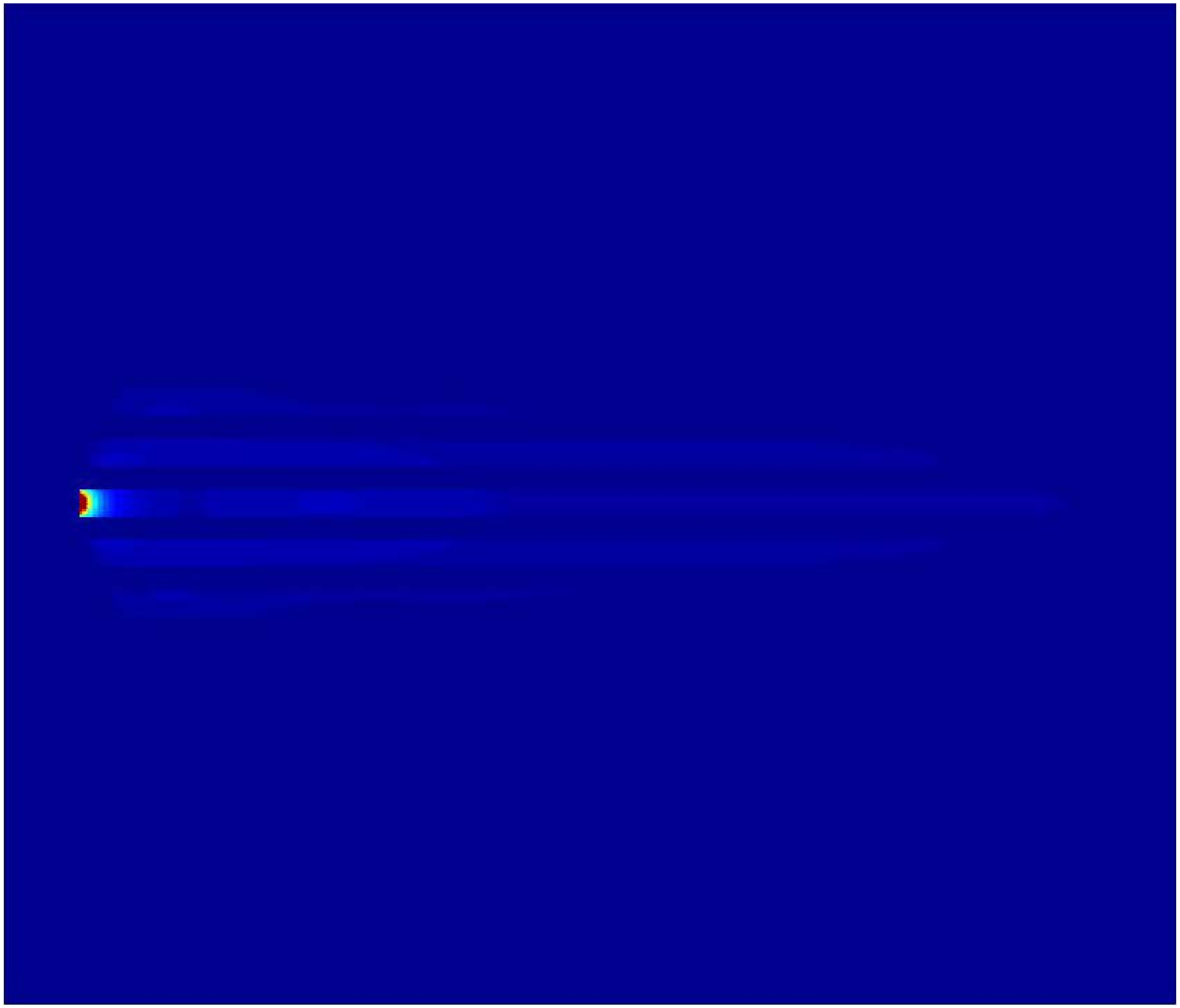
Empty the excited states through an external electric circuit

III. MLME FDTD SIMULATION OF NPD ARRAY



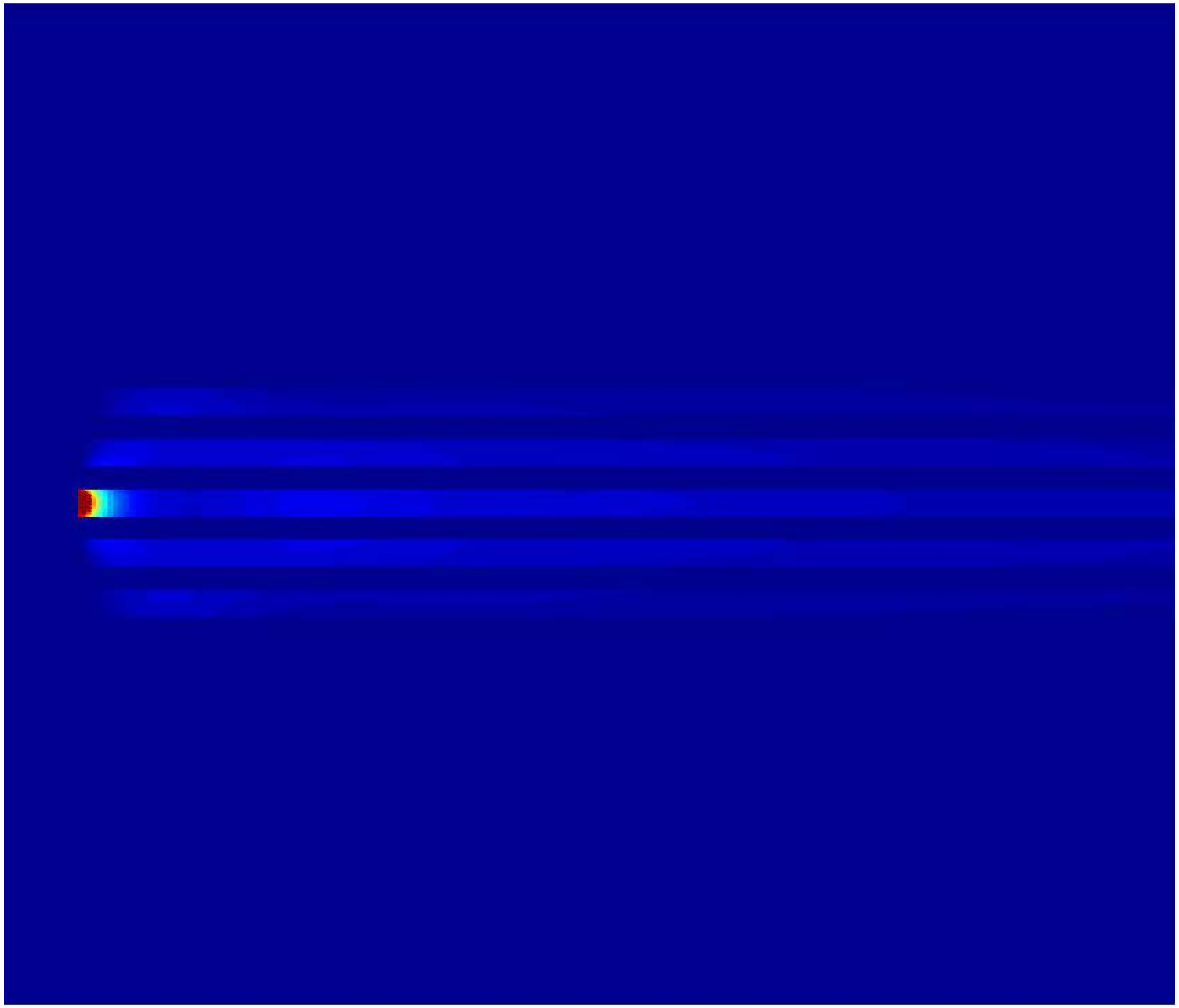
Photocurrent in each pixel

III. MLME FDTD SIMULATION OF NPD ARRAY



Photocurrent in each pixel

III. MLME FDTD SIMULATION OF NPD ARRAY



Photocurrent in each pixel

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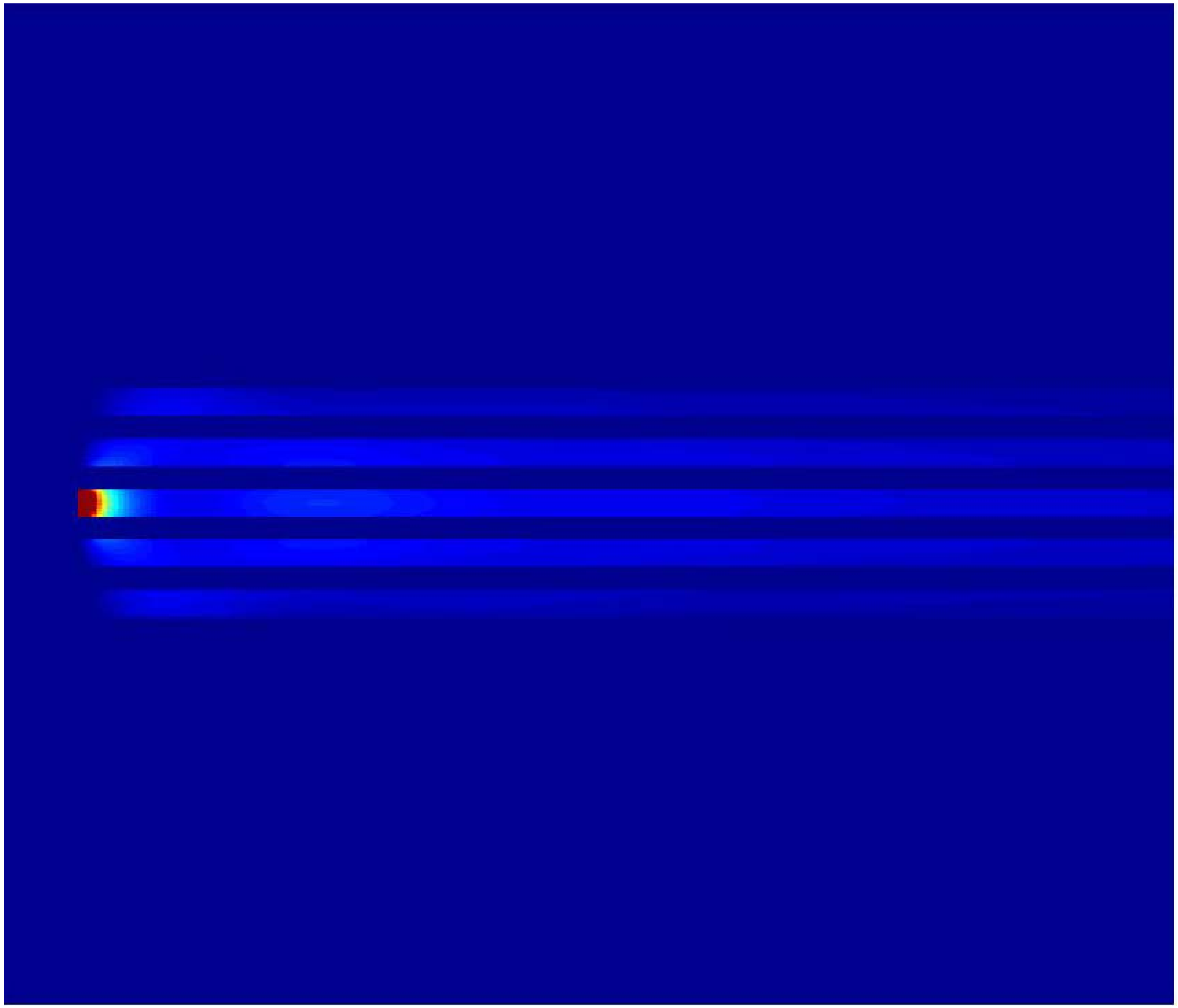

Photocurrent in each pixel

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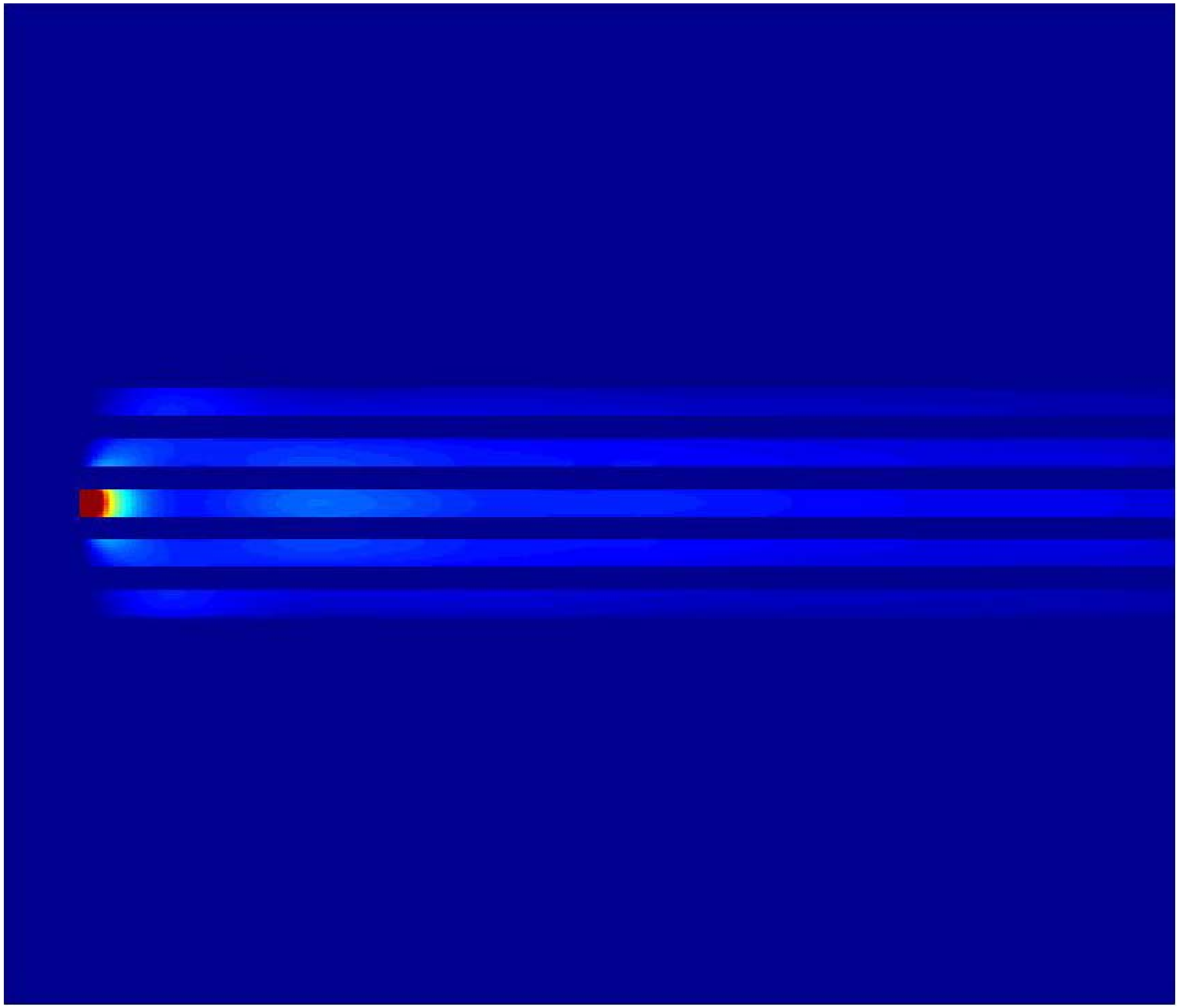

Photocurrent in each pixel

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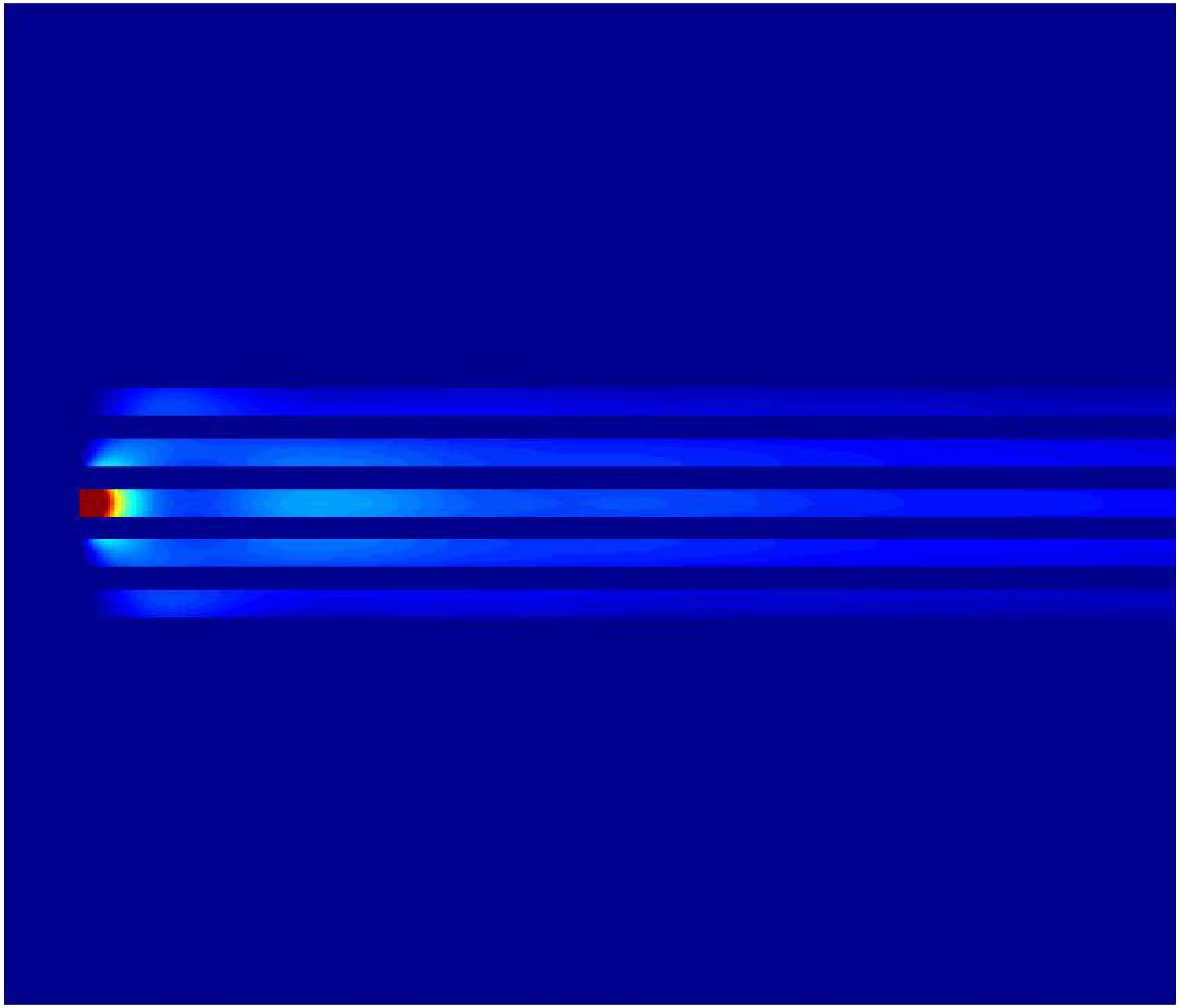

Photocurrent in each pixel

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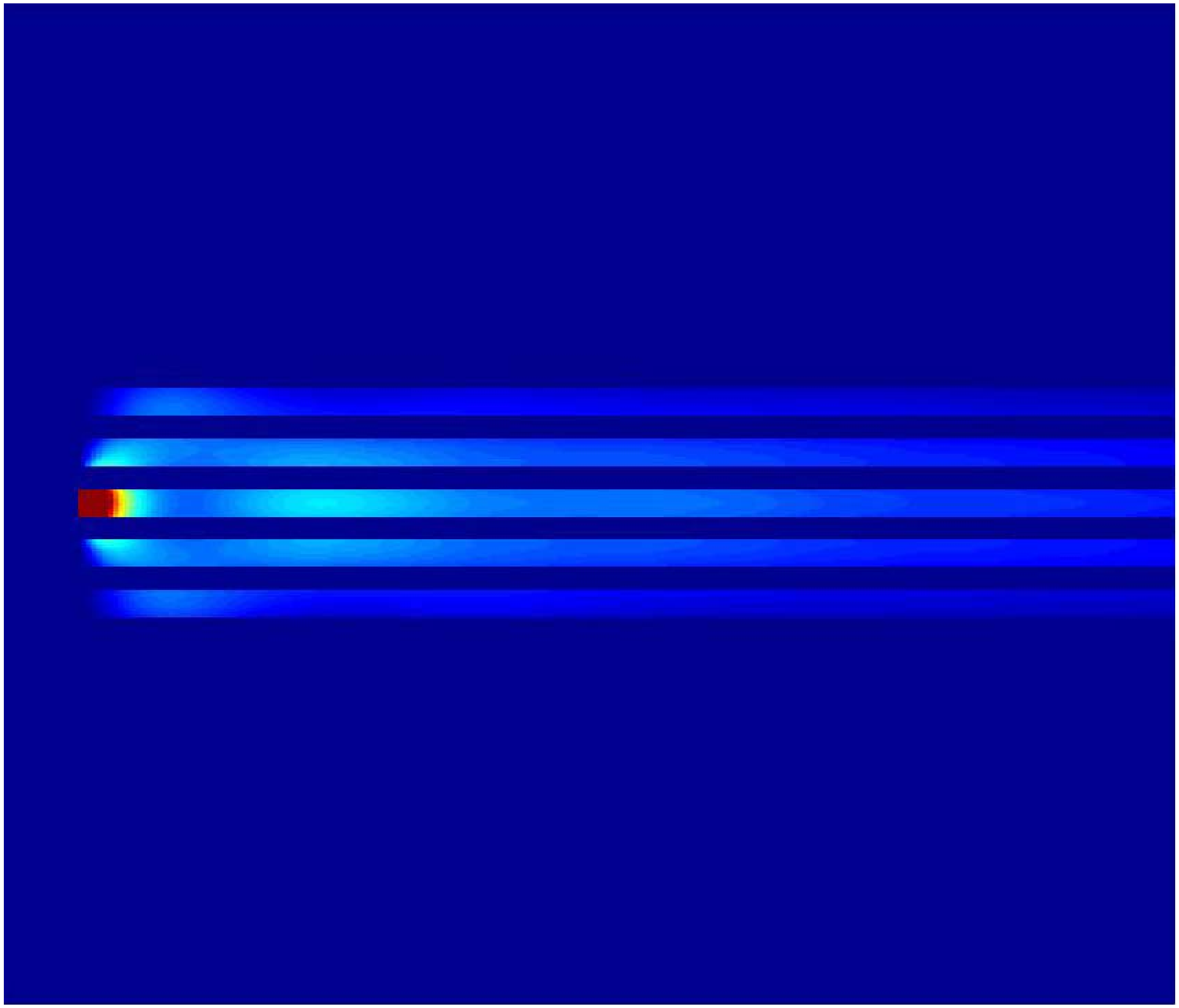

Photocurrent in each pixel

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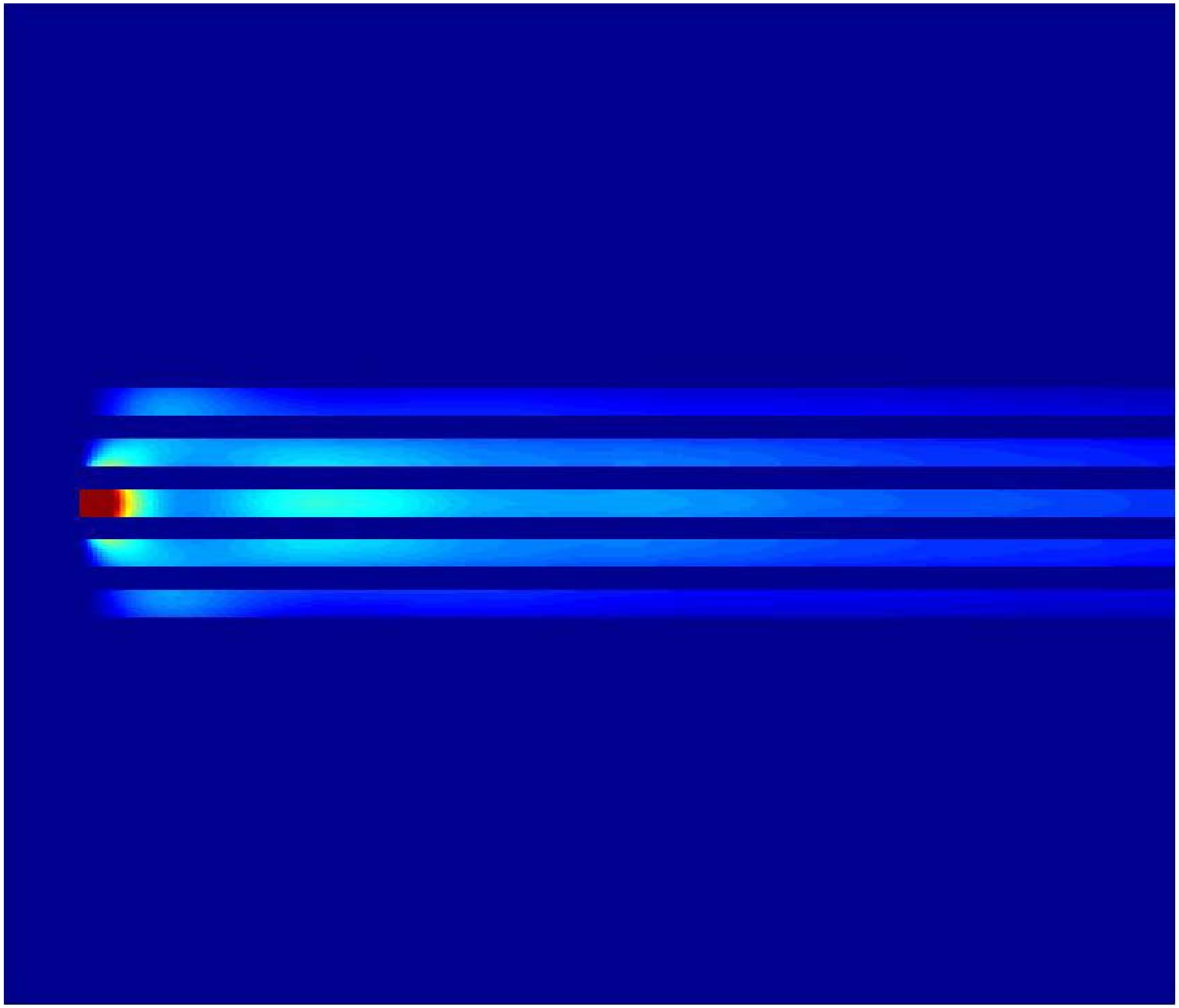
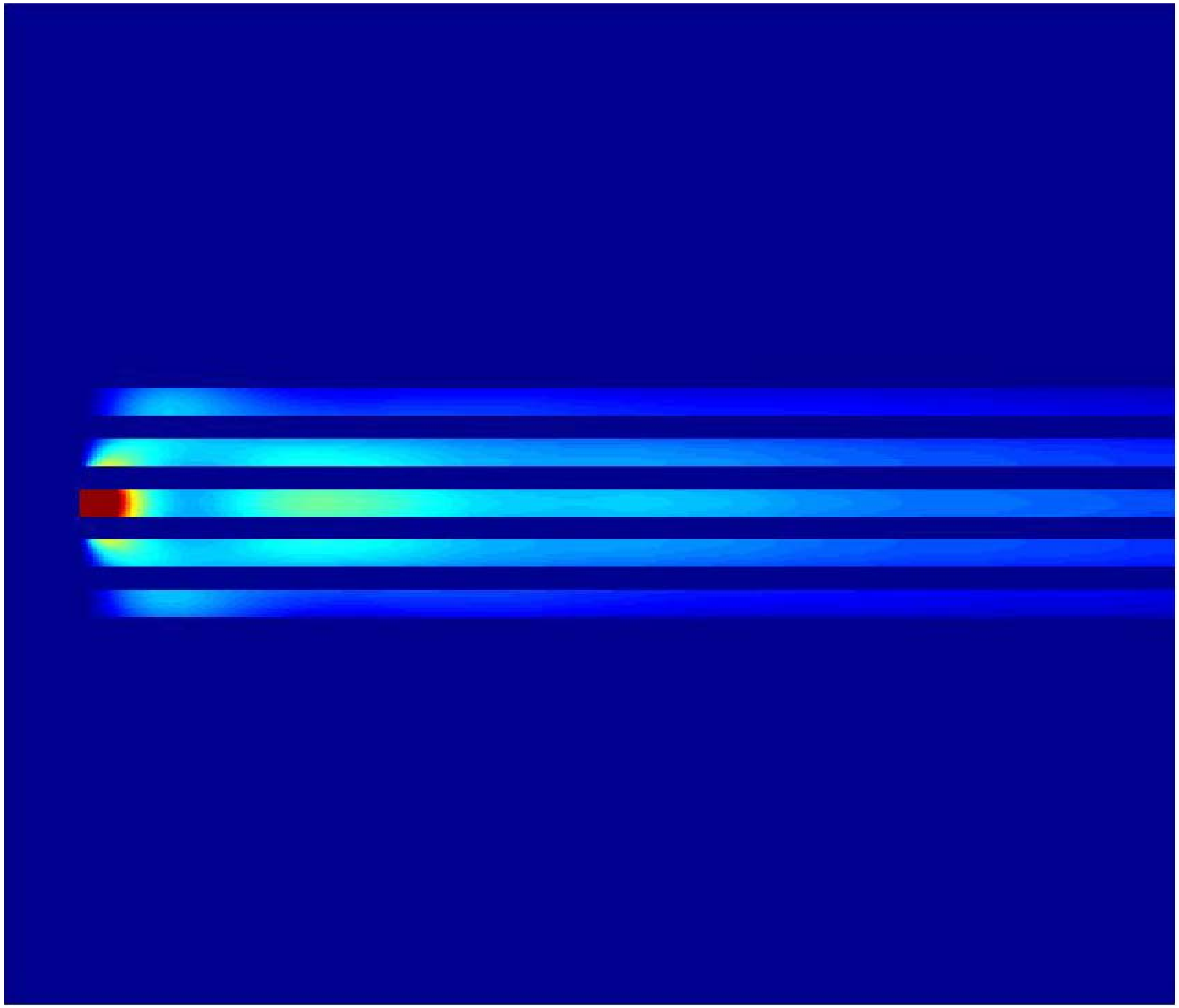


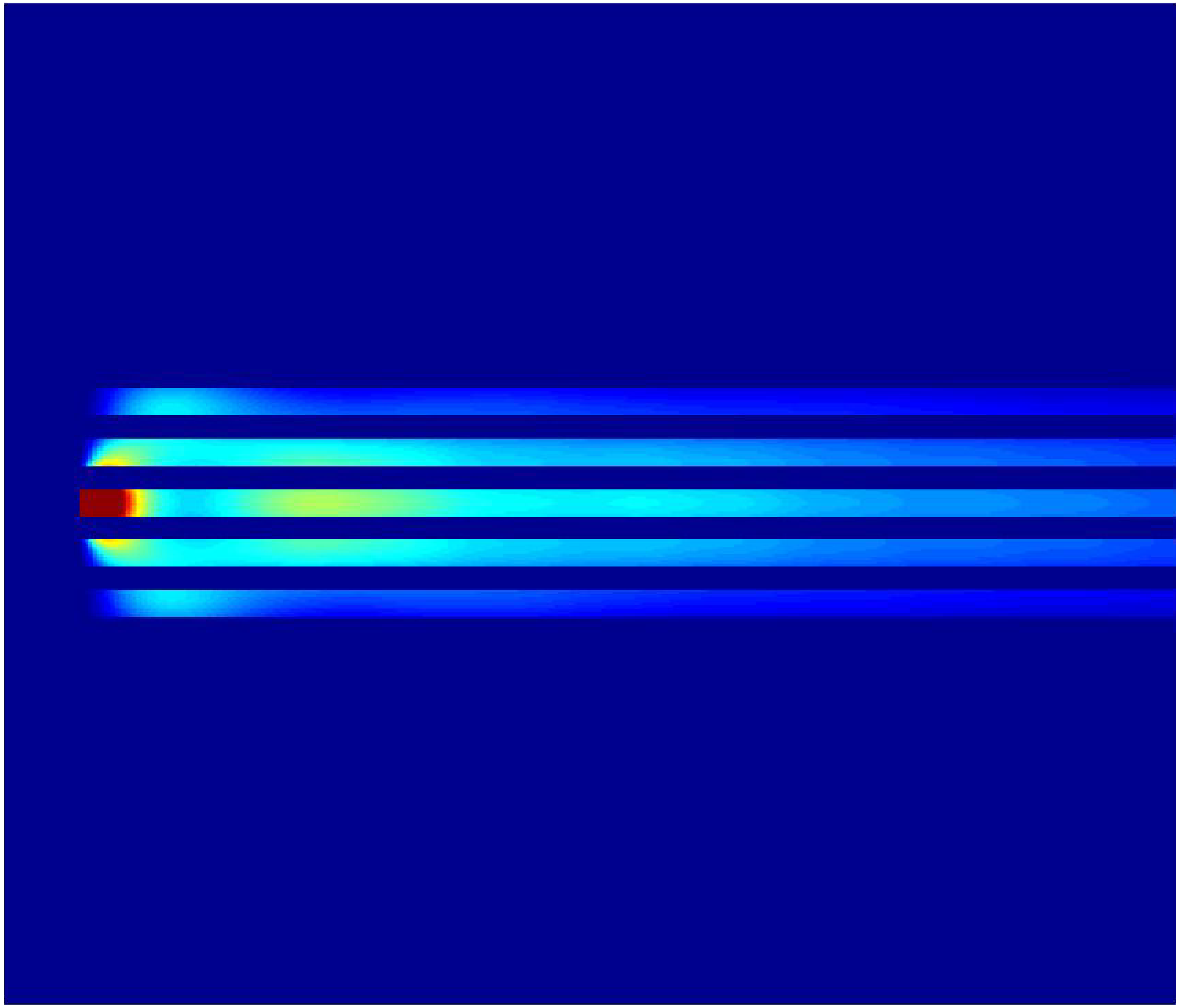
Photocurrent in each pixel

III. MLME FDTD SIMULATION OF NPD ARRAY



Photocurrent in each pixel

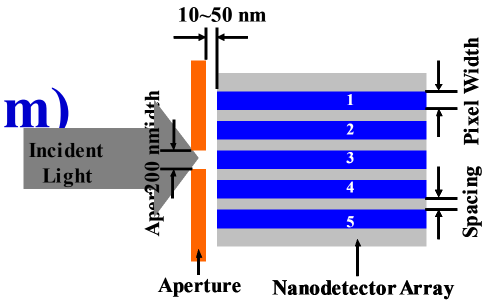
III. MLME FDTD SIMULATION OF NPD ARRAY



Photocurrent in each pixel

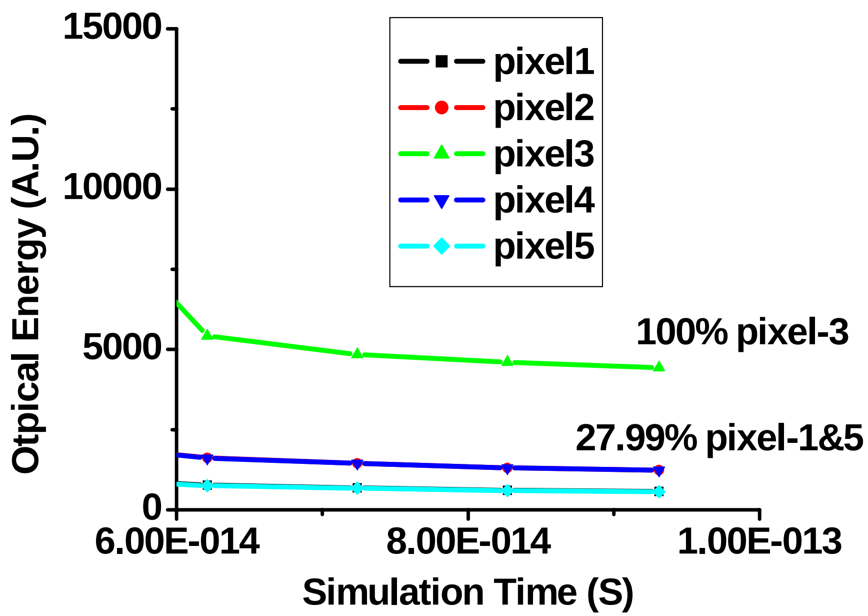
III. MLME FDTD SIMULATION OF NPD ARRAY

- **Results by MLME model FDTD simulation**
  - **Smallest obtainable resolution: 100nm ($\lambda = 1.55\,\mu m$)**

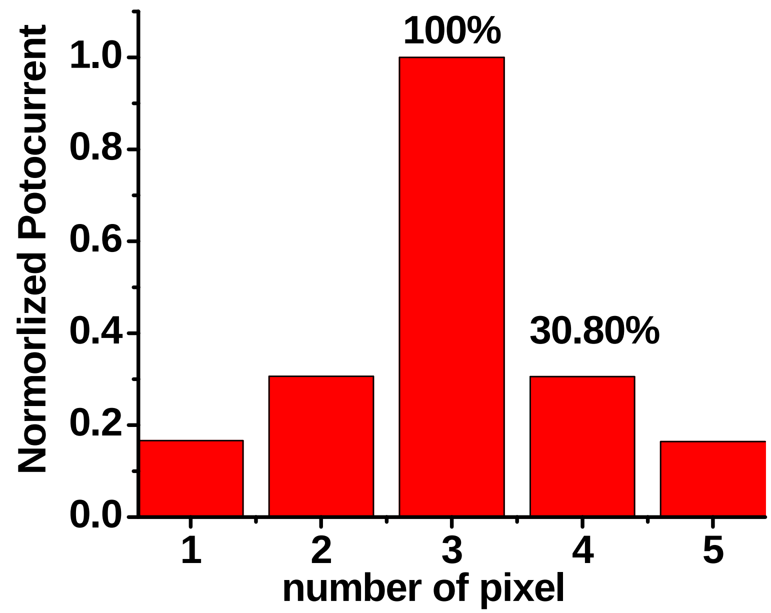


50nm wide and 50nm spacing case

Optical Energy in each pixel



Photocurrent in each pixel



III. MLME FDTD SIMULATION OF NPD ARRAY

- **Summary of FDTD simulation:**
  - **MLME model shows good matching to NPD active material response**
  - **When pixel >100nm, optical coupling between pixels are not dominant**
  - **Smallest obtainable resolution is 100nm for 1.55 μm wavelength**
  - **Correspond to λ/15 for near-IR wavelength.**
  - **Resolution is ~56 times higher than the diffraction limited conventional imaging system in terms of imaging area.**

Conclusion

- We investigated a **simulation method for photodetection in semiconductor medium** with its application to a subwavelength resolvable NPD array.
- A **MLME FDTD method** was employed for the photodetection simulation.
- The FDTD simulation gives us the optical power coupling between the NPD pixels and the spatial distributions of the electric field and the generated photoelectron density, from which the photocurrent can be calculated.
- The NPD can show fine optical resolution that is substantially below the diffraction limit, which can be potentially applied to the observation of nanoscale moving objects or living cells.

Future work

- Prototypes of the NPD array have been developed and the performance tests have been carried out.

B. Liu, Y. Huang, K. Y. Kim, and S. –T. Ho, "Near-field imager based on nanophotodetector array," *Frontiers in Optics 2007 and Laser Science XXIII*, San Jose, California, 16-20 September 2007.

- Further parameter study such as width of metal slit, polarization of incident light, distance between slit and the NPD array, and so on, has been in underway and will be reported somewhere else.

Thank You

Thank you!