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

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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.

• **Photocurrent** 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**.
Basic structures of Nanophotodetector (NPD) Devices:

- Single Detection Pixel
- NPD Array

**λ**

Top Electrode

Semi conductor

Bottom Electrode

Light

Bottom Electrode

Light

Top Electrode

BCB

Semi conductor

BCB

Semi conductor

Light

Light

Light

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II. DEVICE DESIGN FOR NPD ARRAY

- Addressing function:
  - Top and bottom electrode perpendicular to each other, enabling addressing
  - \[ M + N \] electrode stripes \( \rightarrow \) \( M \times N \) addressable pixel array

![Slab Version](image1)

![Channelized Version](image2)

Top view (4 x 4 array)

Top view of channelized 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)
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 = \(w / \text{ccd}\)
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, Simulation of Semiconductor Materials using FDTD method, M. S. Thesis, Northwestern University, 2002
Photocurrent with MLME FDTD method

\[ I_{ph} = \frac{q}{t_{sim}} N \]
\[ = \frac{q}{t_{sim}} \left( \sum_{\text{pixel}} N_2 \right) N_{density} \cdot A \cdot H \]

- \( q \): charge \((1.6 \times 10^{-19} \text{C})\)
- \( t_{sim} \): total time simulated \((1.0 \text{ps})\)
- \( N \): total number of electrons
- \( N_2 \): normalized number of electrons in the upper level
- \( N_{density} \): number of electrons per unit volume \((0.563 \times 10^{22} / \text{m}^3)\)
- \( A \): area of FDTD pixel \((5 \text{nm} \times 5 \text{nm})\)
- \( H \): height of the NPD \((300 \text{nm})\)

Absorption: \(0.5 / \mu\text{m}\)
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
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 $W G \sim \lambda/2(n) \sim \lambda/7$)
Optical coupling between pixels can cause cross talk between adjacent pixels
III. MLME FDTD SIMULATION OF NPD ARRAY

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

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Empty the excited states through an external electric circuit
III. MLME FDTD SIMULATION OF NPD ARRAY

Photocurrent in each pixel
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III. MLME FDTD SIMULATION OF NPD ARRAY

- Results by MLME model FDTD simulation
  - Smallest obtainable resolution: 100nm (λ = 1.55 μm)

50nm wide and 50nm spacing case

Optical Energy in each pixel

Photocurrent in each pixel

![Graph showing optical energy and photocurrent in each pixel](image-url)
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 \( \frac{\lambda}{15} \) 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.


• 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!