Wonseok Shin, Ph.D.

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Contact Information

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Education

Ph.D. in Electrical Engineering (advisor: Prof. Shanhui Fan) — 2013
Stanford University
Dissertation [link]:
"3D Finite-Difference Frequency-Domain Method for Plasmonics and Nanophotonics"

M.S. in Electrical Engineering — 2007
Stanford University

B.S. in Physics & Mathematics — 2001
Seoul National University

Academic Experience

Applied Mathematics Instructor — 2015–present
Department of Mathematics, Massachusetts Institute of Technology

Postdoctoral Associate (mentor: Prof. Steven G. Johnson) — 2015–present
Department of Mathematics, Massachusetts Institute of Technology

Postdoctoral Scholar (mentor: Prof. Shanhui Fan) — 2013–2015
Department of Electrical Engineering, Stanford University

Teaching Experience

Instructor of 18.335: Introduction to Numerical Methods — spring 2016
Department of Mathematics, Massachusetts Institute of Technology
- Course on fundamental theory and techniques of numerical linear algebra.
- Large graduate-level class (45 students)

Instructor of EE 256: Numerical Electromagnetics — spring 2014
Department of Electrical Engineering, Stanford University
- Course on time- and frequency-domain Maxwell's eqs. solvers.
- Rated by students as one of the 10 best EE courses (evaluation: 4.82/5.00).

Industry Experience

Software Engineer — 2001–2004
Park Systems, Suwon, South Korea
Developed the following software for scanning probe microscopes (SPMs):
- Data acquisition software on Texas Instruments' digital signal processor in C
- SPM head control software on Microsoft Windows in C++ (VC++)
- Image editing software (similar to Photoshop) in Java (J2SE)

Honors & Awards

Samsung Scholarship (USD 50,000/year), *Samsung Scholarship Foundation* — 2006–2011
Summa cum laude graduate, *Seoul National University* — 2001
Bronze prize, Collegiate Mathematics Competition, *Korean Mathematical Society* — 1999
Silver medal, Korean Mathematical Olympiad (KMO), *Korean Mathematical Society* — 1994

Patents

W. Shin, S. Fan. "Simulation of phenomena characterized by partial differential equations." Under review by USPTO (application number US 13/744,999) [link].

Research Overview

As an applied mathematician with a background in nanophotonics (a branch of optics that studies the interaction between light and nanometer-scale objects), I have three broad research objectives:

- to develop efficient numerical simulation techniques tailored for specific optical phenomena,
- to design novel nanophotonic components by numerical simulation, and
- to discover underlying principles of nanophotonic phenomena.

I am also interested in applying the same research objectives to the areas related to nanophotonics, such as classical electromagnetics, acoustics, and fluid dynamics.

Accomplishing these research objectives requires deep knowledge in both engineering and applied mathematics. I was fortunate to receive training in both fields at world-leading research institutions during my doctoral (Electrical Engineering at Stanford University) and postdoctoral (Applied Mathematics at MIT) research periods. In what follows, I describe each research objective in more detail and highlight my achievements.

Efficient numerical simulation techniques tailored for specific optical phenomena

My main research objective is to develop numerical simulation techniques tailored for specific physical phenomena to simulate. Though physical phenomena in a given engineering domain (e.g., nanofluidics or nanophotonics) are always dictated by the same governing equations (e.g., the Navier-Stokes equations or Maxwell's equations), mathematical properties of these equations vary significantly depending on the specific phenomena to simulate. By taking advantage of the governing equations' special properties manifested in the phenomena of interest, the numerical solution of these equations can be obtained order-of-magnitude faster.

For example, I developed efficient techniques for solving Maxwell's equations for a branch of nanophotonics called *plasmonics*. The defining feature of plasmonics is that the wavelength of light shrinks greatly inside plasmonic materials (such as metals) as a result of coupling of light with the collective motion of free electrons. Because the wavelength inside and outside plasmonic materials are so different (e.g., 1 μm vs. 10 nm), the problem becomes *spatially multiscale*. In numerical solvers, this leaves the differential operator (a) ill-conditioned and (b) with lots near-zero eigenvalues. Both characteristics of the differential operator slow down the convergence of iterative solvers widely used for solving a large system of linear equations.

To accelerate the convergence of iterative solvers, I developed two techniques that specifically address the difficulties arising in plasmonics. First, I developed a preconditioner that alleviates the ill-conditioning originating from the multiple length scales in plasmonics [*J. Comput. Phys.* 2012]. This technique alone achieved more than *150X* speedup and made iterative solvers practical for plasmonics. Second, I combined Maxwell's equations with the charge-current continuity equation to distribute the near-zero eigenvalues elsewhere [*Opt. Express* 2013]. This eliminated stagnation in the convergence of iterative solvers and achieved additional 2X speedup.

As another example, I developed a method for solving Maxwell's equations for *active* nanophotonic components. In this case, the problems are *temporally mulitscale* because the optical properties of active components are modulated at much slower frequencies than the optical signals' frequencies (e.g., gigahertz modulation vs. terahertz signals). Conventional time-domain methods are prohibitively inefficient for such multi-time-scale problems, because they must simulate thousands of optical cycles to complete even a single modulation cycle. To overcome this specific difficulty, I developed a frequency-domain method that is capable of handling multiple sideband frequencies introduced by modulation [*Optica* 2016]. Because this is a frequency-domain method, it produces the steady-state solution without having to wait for thousands of optical cycles to pass, and hence allows efficient study of novel nanophotonic components, such as optical isolators, that require active modulation.

Novel nanophotonic component designs

With my efficient numerical simulation techniques, my collaborators and I were able to design novel nanophotonic components by performing more accurate, larger-scale simulation that had been impossible with conventional methods. For example, we designed

- microlenses in submicron-thin metallic films [*Opt. Lett.* 2010],
- 90° bends and T-splitters to route optical signals on-chip [*Adv. Mater.* 2010, *Nano Lett.* 2013],
- grating couplers to launch surface plasmons into only one direction [*Nano Lett.* 2014],
- image sensors to detect three colors in a single pixel [*Appl. Phys. Lett.* 2014, *ACS Photonics* 2017],
- plasmonic waveguide stub filters [*Opt. Express* 2015], and
- microfluidic channels to trap and release particles optically [*Lap Chip* 2016].

Underlying principles of nanophotonic phenomena

I am also interested in understanding the underlying principles of nanophotonic phenomena. My research toward this objective branches into two directions. The first direction is to find intuitive models explaining nanophotonic phenomena. Though all nanophotonic phenomena are dictated completely by Maxwell's equations, it is often possible to explain them with simpler and more intuitive models. Such models provide useful guidance in designing nanophotonic components: the circuit model for plasmonic waveguides [*Nano Lett.* 2013] and the interference model for grating couplers [*Nano Lett.* 2014] are good examples.

The second direction toward this objective is about understanding general limits of the performance of nanophotonic components. One of such limits is imposed by the energy loss rates inside plasmonic materials. Though the use of plasmonic materials has provided extra degrees of freedom to nanophotonic component design, it has one critical problem: severe energy loss. Light coupled with free electrons in plasmonic materials loses its energy quickly through scattering of the coupled free electrons, and such energy loss deteriorates the performance of nanophotonic components.

To understand the behavior of the energy loss, I first derived detailed analytic expressions of electromagnetic energy and its loss rates [*J. Opt. Soc. Am. B* 2012]. Using these expressions, then I derived a fundamental upper bound of energy loss rates in plasmonic materials [*Phys. Rev. Lett.* 2013]. Lastly, I showed that the upper bound can be lowered at microwave frequencies [*Appl. Phys. Lett.* 2015]. Such characterization of the behavior of energy loss should be useful for predicting and improving the performance of nanophotonic components.

Refereed Journal Publications

Computational Techniques

3. Y. Shi, W. Shin, S. Fan. "Multi-frequency finite-difference frequency-domain algorithm for active nanophotonic device simulations." *Optica* **3** (2016): 1256–59 [link].
2. W. Shin, S. Fan. "Accelerated solution of the frequency-domain Maxwell's equations by engineering the eigenvalue distribution of the operator." *Optics Express* **21** (2013): 22578–95 [link].
1. W. Shin, S. Fan. "Choice of the perfectly matched layer boundary condition for frequency-domain Maxwell's equations solvers." *Journal of Computational Physics* **231** (2012): 3406–31 [link].

Nanophotonic Component Designs

8. Y. Büyükalp, P. B. Catrysse, W. Shin, S. Fan. "Planar, ultra-thin, subwavelength spectral light separator for efficient, wide-angle spectral imaging." *ACS Photonics* (2017): in press [link].
7. S. A. Khan, C.-M. M. Chang, Z. Zaidi, W. Shin, Y. Shi, A. K. Ellerbee Bowden, O. Solgaard. "Metal-insulator-metal waveguides for particle trapping and separation." *Lab on a Chip* **16** (2016): 2302–8 [link].
6. A. Mahigir, P. Dastmalchi, W. Shin, S. Fan, G. Veronis. "Plasmonic coaxial waveguide-cavity devices." *Opt. Express* **23** (2015): 20549–62 [link].
5. Y. Büyükalp, P. B. Catrysse, W. Shin, S. Fan. "Spectral light separator based on deep-subwavelength resonant apertures in a metallic film." *Applied Physics Letters* **105** (2014): 011114 [link].
4. T. Liu*, Y. Shen*, W. Shin*, Q. Zhu, S. Fan, C. Jin. "Dislocated double-layer metal gratings: an efficient unidirectional coupler." *Nano Letters* **14** (2014): 3848–54 [link] (***co-first authors**).

3. W. Shin, W. Cai, P. B. Catrysse, G. Veronis, M. L. Brongersma, S. Fan. "Broadband sharp 90-degree bends and T-splitters in plasmonic coaxial waveguides." *Nano Letters* **13** (2013): 4753–58 [link].
2. W. Cai, W. Shin, S. Fan, M. L. Brongersma. "Elements for plasmonic nanocircuits with three-dimensional slot waveguides." *Advanced Materials* **22** (2010): 5120–24 [link].
1. L. Verslegers, P. Catrysse, Z. Yu, W. Shin, Z. Ruan, S. Fan. "Phase front design with metallic pillar arrays." *Optics Letters* **35** (2010): 844–46 [link].

Fundamental Physics

4. W. Shin, S. Fan. "Unified picture of modal loss rates from microwave to optical frequencies in deep-subwavelength metallic structures: A case study with slot waveguides." *Applied Physics Letters* **107** (2015): 171102 [link].
3. A. Raman, W. Shin, S. Fan. "Metamaterial band theory: fundamentals & applications." *Science China Information Sciences* **56** (2013): 1–14 [link].
2. A. Raman, W. Shin, S. Fan. "Upper bound on the modal material loss rate in plasmonic and metamaterial systems." *Physical Review Letters* **110** (2013): 183901 [link].
1. W. Shin, A. Raman, S. Fan. "Instantaneous electric energy and electric power dissipation in dispersive media." *Journal of Optical Society of America B* **29** (2012): 1048–54 [link].

Conference Oral Presentations

4. W. Shin, W. Cai, P. B. Catrysse, G. Veronis, M. L. Brongersma, S. Fan. "Plasmonic nano-coaxial waveguides for 90-degree bends and T-splitters." *CLEO*, San Jose, California. June 2013.
3. W. Shin, S. Fan. "Choice of the perfectly matched layer boundary condition for iterative solvers of the frequency-domain Maxwell's equations." *28th Annual Review of Progress in Applied Computational Electromagnetics*, Columbus, Ohio. Apr. 2012.
2. W. Shin, S. Fan. "Accelerated solution of the frequency-domain Maxwell's equations by engineering the spectrum of the operator using the continuity equation." *12th Copper Mountain Conference on Iterative Methods*, Copper Mountain, Colorado. Mar. 2012.
1. W. Shin, S. Fan. "Choice of the perfectly matched layer boundary condition for iterative solvers of the frequency-domain Maxwell's equations." *SPIE Photonics West*, San Francisco, California. Jan. 2012.

Conference Poster Presentations

2. W. Shin, A. Raman, S. Fan. "Upper bound on the modal material loss rate in plasmonic and metamaterial systems." *First Year Review of AFOSR MURI: Template-Directed Directionally Solidified Eutectic Metamaterials*, Dayton, Ohio. Oct. 2013.
1. W. Shin, A. Raman, S. Fan. "Instantaneous electric energy density and power dissipation density in dispersive media." *IONS NA-3*, Stanford, California. Oct. 2011.

Academic Software Development

MaxwellFDFD *developed in MATLAB* http://www.mit.edu/~wsshin/maxwellfdfd.html

MaxwellFDFD is a MATLAB-based package that solves the frequency-domain Maxwell's equations. It constructs a system of linear equations out of Maxwell's equations by the finite-difference frequency-domain (FDFD) method, and hence the name MaxwellFDFD. The constructed system is solved by MATLAB's built-in direct solvers. MaxwellFDFD has the following major features:

- Adaptive nonuniform grid generation aligned with object boundaries
- Waveguide mode solver and waveguide-mode-generating current source
- 2D and 3D visualization of objects, sources, and solution fields
- Periodic array of objects
- Electric ($\mathbf{J}$) and magnetic ($\mathbf{M}$) current sources
- PEC, PMC, periodic, and Bloch boundary conditions
- Stretched-coordinate perfectly matched layer (SC-PML) and uniaxial PML (UPML)
- Total-field/scattered-field (TF/SF) method
- Power flux calculation

FD3D *developed in C and Python using PETSc* http://www.mit.edu/~wsshin/fd3d.html

FD3D is a parallelized computational kernel for solving the frequency-domain Maxwell's equations. It is a companion program of MaxwellFDFD: users can easily generate the input files for FD3D from MaxwellFDFD, and import the solution calculated by FD3D into MaxwellFDFD for further analysis. FD3D uses PETSc for matrix and vector management, and it runs on any LINUX clusters that support MPI communication. FD3D is also equipped with Python scripts for spectrum analysis. Unlike MaxwellFDFD, FD3D solves the constructed system of linear equations by Krylov iterative solvers rather than direct solvers to avoid large memory consumption. Using the various techniques developed throughout my doctoral research, FD3D achieves more than 300-fold speedup compared with conventional iterative solvers of the frequency-domain Maxwell's equations.

jemdoc+MathJax *developed in Python* http://www.mit.edu/~wsshin/jemdoc+mathjax.html

jemdoc is an open-source website generator that is widely used in the academia for generating personal and course websites. *MathJax* is an open-source project founded by AMS and SIAM for displaying LaTeX equations on webpages. Combining these two existing platforms, I have developed *jemdoc+MathJax*, an open-source program for easily creating academic websites containing complex LaTeX equations. See my interview with MathJax.org about jemdoc+MathJax [link].

References

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