Program Objective

Integrate quantum emitters with optical metamaterials to expand & redefine the range of light-matter interactions & electronic excitations available for solid-state quantum optics.
Metamaterials: Scaling and Sculpting Electromagnetic Modes

**Sub-Wavelength Cavities**

Yang et al., *Nature Photon.* 6, 450 (2012)


**Epsilon-Near-Zero Waveguides**


Ko et al., *Nano Lett.* 11, 61 (2011)

**Resonant Optical Antennas**

**Optical Antenna Arrays**
At the quantum level, *both the strength & nature of light-matter interactions* are limited by the size mismatch between the optical wavelength & electronic emitters.

**Quantum Metaphotonics:**
*Enhancing microscopic light-matter interactions with single emitters* using subwavelength cavities and antennas to access new regimes of cavity QED.

**Quantum Metamaterials:**
*Enabling collective excitations in dense emitter ensembles* using extended modes in epsilon-near-zero waveguides and antenna arrays.
Quantum Metamaterials & Metaphotonics (QMM) MURI Team

Expertise in Metamaterials, Plasmonics, Quantum Optics, and Solid-State Quantum Emitters

Harry Atwater, CalTech
1 GS + 1 PD

Seth Bank, UT Austin
1 GS + 0.5 PD

Mark Brongersma, Stanford
2 GS

Shanhui Fan, Stanford
2 GS

Nader Engheta, U Penn
1 GS + 1 PD

Nicholas Fang, MIT
1 GS + 1 PD

Arto Nurmikko, Brown
2 GS

Jelena Vuckovic, Stanford
1 GS + 1 PD

Xiang Zhang, UC Berkeley
1 PD + 0.5 GS

Rashid Zia, Brown
2 GS
Goal: Use metamaterials and nanophotonics to expand and redefine the range of light-matter interactions and electronic excitations for solid-state quantum optics.

**Theory:**
Quantum transport theory of few-photon Fock states

**Materials:**
Composite Epsilon-near-zero at VIS & NIR wavelengths

**Devices:**
On-chip plasmon quantum interference experiments.

**Fan (Stanford)**

**Polman (AMOLF) & Engheta (UPenn)**

**Atwater (Caltech)**
Quantum Transport Theory of Few-Photon Fock States

The Fan group has developed rigorous theoretical tools to study the transport properties of few-photon Fock states in quantum nanophotonic structures.

Adopting the input-output theory in quantum optics for the study of Fock state transport, they have:

- Calculated the exact two-photon scattering matrix (S-matrix) of two-photon Fock states propagating through a waveguide coupled to a whispering gallery mode resonator containing a two-level atom.

- Developed formalism to account for the effects of loss (dissipation) rigorously in few-photon transport.

This theory intuitively highlights the origins and implications of strong photon-photon correlations in coupled atom-waveguide systems.

Wide-Angle Energy-Momentum Spectroscopy

The Zia group has developed a new spectroscopic technique for characterizing the wavelength and polarization dependent radiation patterns of quantum emitters and optical nanostructures.

This new spectroscopic technique allows for:

- Simultaneous measurement of the polarized radiation patterns at every wavelength within the measurement domain.
- Improved optical throughput by orders of magnitude without sacrificing spectral resolution.
- Determination of contributions to emission/scattering in any system with well defined basis functions.

Two-Plasmon Hong-Ou-Mandel Quantum Interference

Results demonstrate:

- Surface plasmons exhibit Hong-Ou-Mandel interference without any significant reduction in visibility or coherence.
- Plasmonic quantum interference is identical to the dielectric case.
- Dispersion and dephasing in plasmonic structures does not affect the visibility of interference.

Resonantly Phase-Matched Traveling Wave Parametric Amplifier

By leveraging metamaterial-based dispersion engineering, the Zhang group has designed broadband, high gain, near quantum noise limited parametric traveling wave amplifiers.

Using a traveling wave amplifier and introducing a metamaterial in the line has allowed for:

- Resonantly phase matching the signal and pump beams leading to exponential gain (>20dB in the proposed device)
- A wide bandwidth compared to traditional cavity based amplifier (3GHz compared to a few MHz)

Team Activities: Catalyzing and Strengthening Collaborations

2 Team Reviews

- MURI Kickoff in Arlington, September 2012
- Year 1 Review in Arlington, January 2014

2 Conference Satellite Workshops

- Workshop at MIT following Fall 2012 MRS
- Workshop at Stanford before Spring 2013 MRS

30+ Team Webinars and Web Meetings

- Tutorial Presentations by:
  - Nader Engheta on "Extreme Parameter Metamaterials"
  - Luke Sweatlock on "Numerical Optimization"
- Research Presentations from every group
- Special Research Highlight Presentations by
  - Pankaj Jha on "Coherence-Enhanced Spasers"
  - Ruzan Sokhoyan on "Superradiance in ENZ Metamaterials"
- Working Group Discussions, including
  - Regular biweekly meetings examining boundaries between quantum & classical phenomena (Quantum/Classical WG led by Jim Fakonas)
  - Journal and Book Club discussions on recent papers as well as canonical books (e.g. Mandel & Wolf on collective atomic interactions and cooperative effects)

Numerous Multidisciplinary Collaborations, Discussions, Exchanges, Visits, etc.

- Advising and Mentoring Students
  Luke Sweatlock (NGC) advising students at Caltech on metamaterial parameter retrieval and MIM designs; Engheta and Caglayan advising Brown students on how to design and measure emitters in ENZ waveguides; etc.

- Exchanging Expertise and Ideas
  Bank’s sabbatical at Stanford working with Brongersma & Vuckovic and visit with Zhang at Berkeley; Atwater group sharing recipes on epitaxial lift-off with Brown; ENZ superradiance and superfluorescence discussions involving Berkeley, Brown, Caltech, & U Penn; etc.

- Sharing Code and Equipment
  Fan & Vuckovic groups collaborating to develop and maintain 3D FDFD GPU-based simulation codes; Zia lab lending monolayer deposition system to Fang group; etc.

- Swapping Materials and Samples
  Bank’s group providing epitaxial QDs to Vuckovic & Zia groups and epitaxial plasmonic materials to Brongersma group; Zia group providing transition-metal and rare-earth ion emitter samples to Berkeley and Stanford; etc.

- Taking on Larger Scientific Problems

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Including 6 Nano Letters, 2 Nature Photonics, and 2 Physical Review Letters to date


Team Output: 22 Publications in leading scientific journals

Including 6 Nano Letters, 2 Nature Photonics, and 2 Physical Review Letters to date


Wagner et al., “Ultrafast Dynamics of Surface Plasmons in InAs by Time-Resolved Infrared Nanospectroscopy”, Nano Lett. (2014), Article ASAP.


All Publication Information available at www.QuantumMetaphotonics.com

Including 6 Additional arXiv Preprints under review or in press.


Karaveli et al., “Probing the electromagnetic local density of states with a strongly mixed electric and magnetic dipole emitter” arXiv:1311.0516.


Recent Team Awards, News Highlights, and Successful Alums

Awards and Honors

- Harry Atwater, Founding Editor-in-Chief ACS Photonics
- Nader Engheta, Inaugural SINA Award in Engineering and the Benjamin Franklin Key Award from IEEE Philadelphia
- Jelena Vuckovic, Hans Fischer Senior Fellowship from the Technical University Munich – Institute for Advanced Studies

News Highlights

- Nature Photonics News & Views feature on graphene nanoresonators from Atwater group
- Materials Today podcast with Rashid Zia on energy-momentum spectroscopy

Successful MURI Team Alums

- Arka Majumdar (Vuckovic group alum) is now an Assistant Professor of Physics at the University of Washington.
- Humeyra Caglayan (Engheta group alum) is now an Assistant Professor of Electrical Engineering at Abdullah Gul University
- Sinan Karaveli (Zia group alum) won Outstanding Dissertation Award and is now a Postdoctoral Researcher at MIT.
- Eden Raphaeli (Fan group alum) is now a Research Hardware Engineer at Google X.
- David Schoen (Brongersma group alum) is now a Research Scientist at Exponent Failure Analysis.
- Xiaobo Yin (Zhang group alum) is now an Assistant Professor of Mechanical Engineering at the University of Colorado Boulder.
Thank you.