QUANTUM Metamaterials & Metaphotonics MURI

Quantum Metaphotonics & Metamaterials: From Single Emitters to Strongly Correlated Systems

Rashid Zia, Brown University

AFOSR Program Managers: Harold Weinstock & Gernot Pomrenke

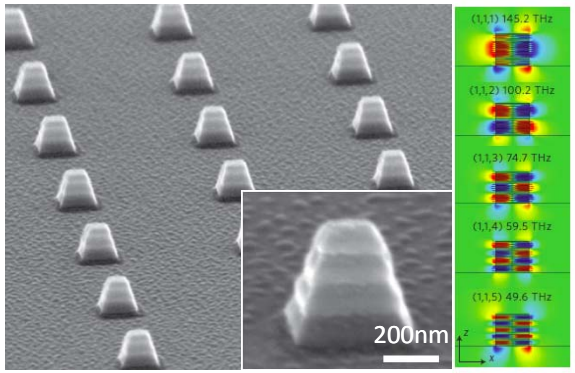
July 29, 2014

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.

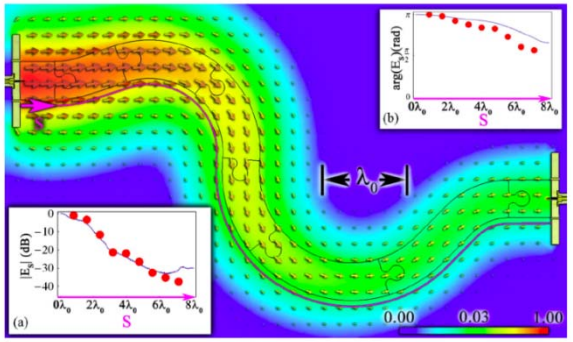
Metamaterials: Scaling and Sculpting Electromagnetic Modes

Sub-Wavelength Cavities

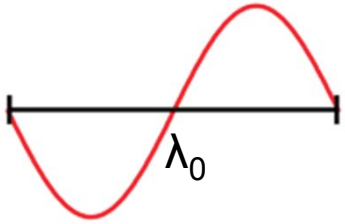


Yang *et al.*, *Nature Photon.* 6, 450 (2012)

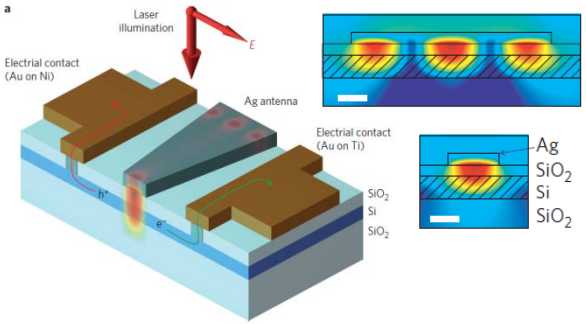
Epsilon-Near-Zero Waveguides



Edwards & Engheta,
Phys. Rev. Lett. **108**, 193902 (2012)

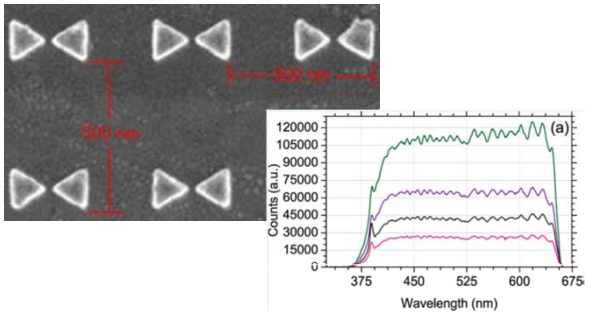


Barnard, Pala & Brongersma,
Nature Nanotech. 6, 588 (2011)



Resonant Optical Antennas

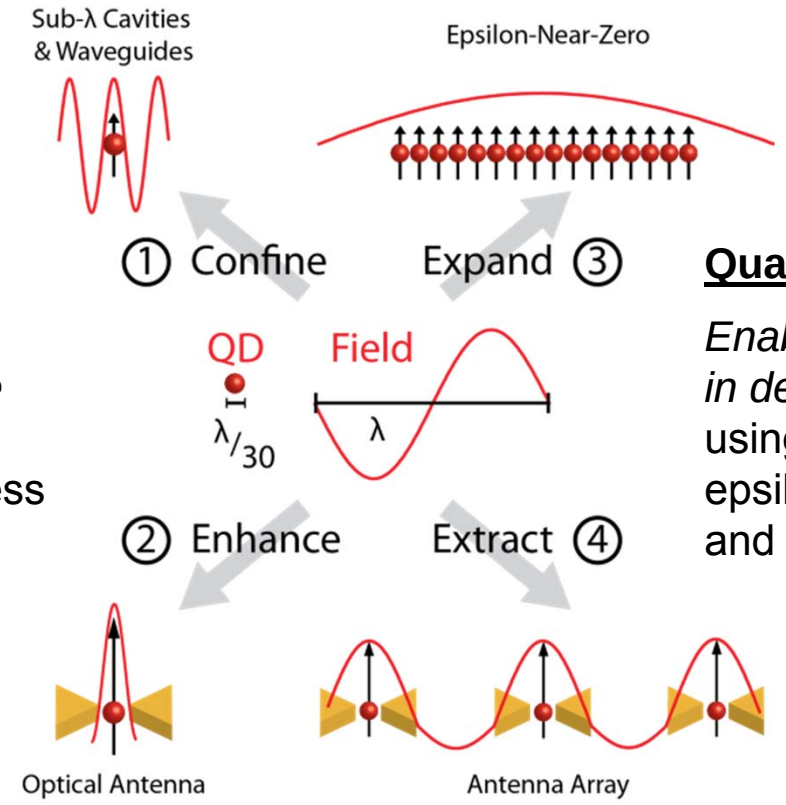
Ko *et al.*, *Nano Lett.* 11, 61 (2011)



Optical Antenna Arrays

Addressing the Size Mismatch between Emitters & Optical Fields

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

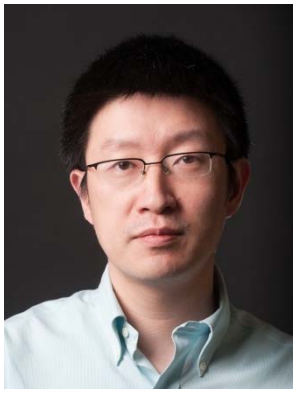
Harry Atwater,
CalTech
1 GS + 1 PD

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

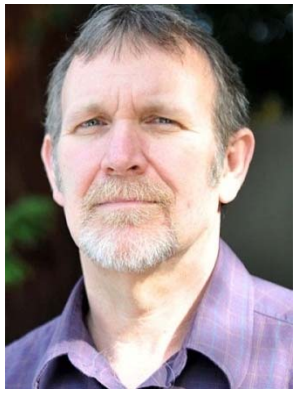
Rashid Zia,
Brown
2 GS

QUANTUM Metamaterials & Metaphotonics MURI

Quantum Metamaterials & Metaphotonics (QMM) MURI Team

Industrial Collaborators

HP Labs
Ray Beausoleil



NORTHROP GRUMMAN

Northrop Grumman
Luke Sweatlock

International Partners

AMOLF FOM

AMOLF
Albert Polman

ICFO
The Institute of Photonic Sciences

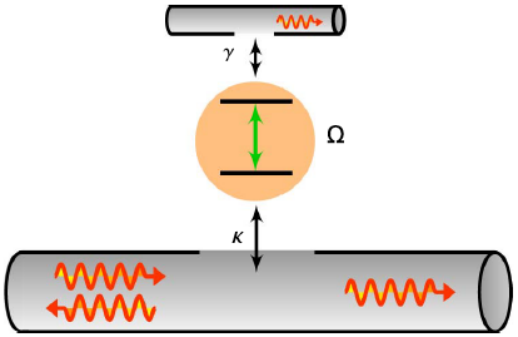
ICFO
Niek van Hulst

Reexamining the Theory, Materials, and Devices for Photonics & Quantum Optics

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

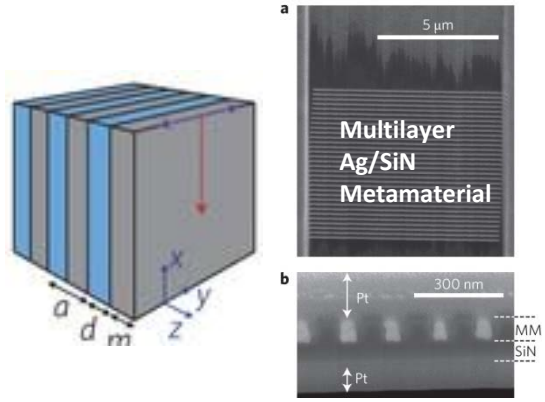


Fan (Stanford)

Rephaeli & Fan, *Photon. Res.* 1 (2013), 110.
Shi & Fan, *PRA* 87 (2013), 063818.
Xu, Rephaeli & Fan, *PRL* 111 (2013), 223602.

Materials:

Composite Epsilon-near-zero at VIS & NIR wavelengths

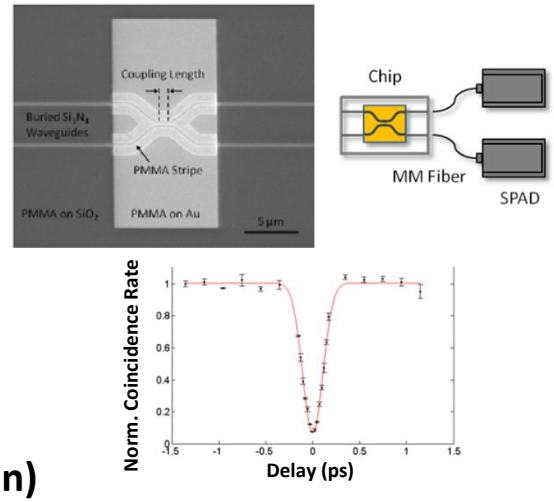


Polman (AMOLF) & Engheta (UPenn)

Mass, Parsons, Engheta & Polman,
Nature Photonics 7 (2013), 907.

Devices:

On-chip plasmon quantum interference experiments.

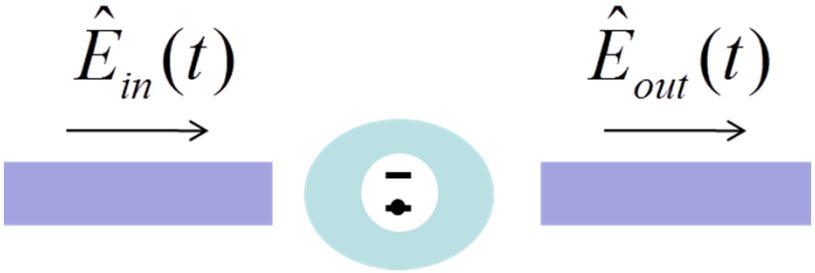


Atwater (Caltech)

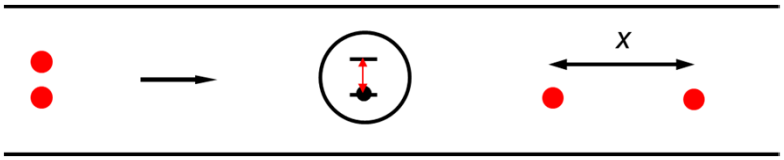
Fakonas, Lee, Kelaita & Atwater,
Nature Photonics 8 (2014) , 317.

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.



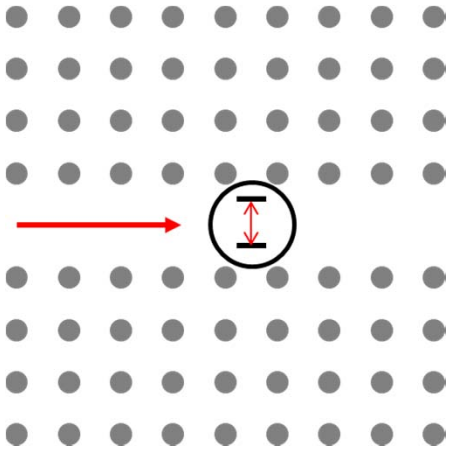
Two-Level Atom in Waveguide



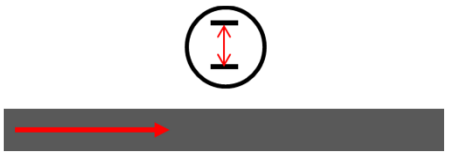
Adoping the input-output theory in quantum optics for the study of Fock state transport, they have:

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



Photonic Crystal

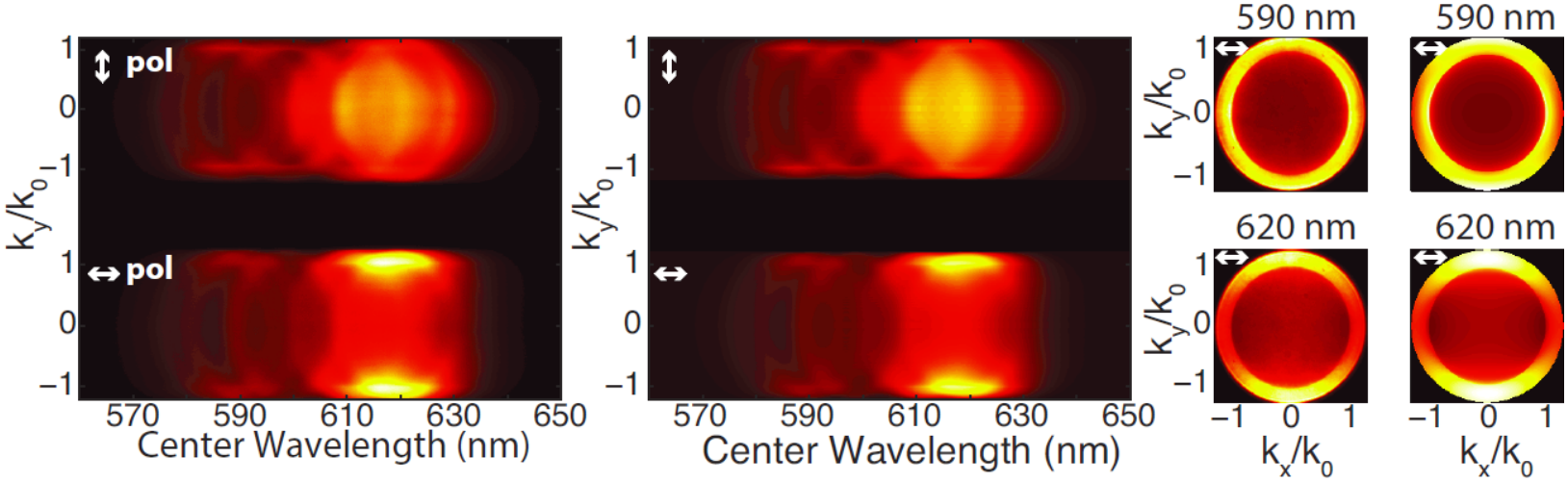


Plasmonic Nanowire

Rephaeli & Fan, *Photon. Res.* 1 (2013), 110. Shi & Fan, *PRA* 87 (2013), 063818. Xu, Rephaeli & Fan, *PRL* 111 (2013), 223602.

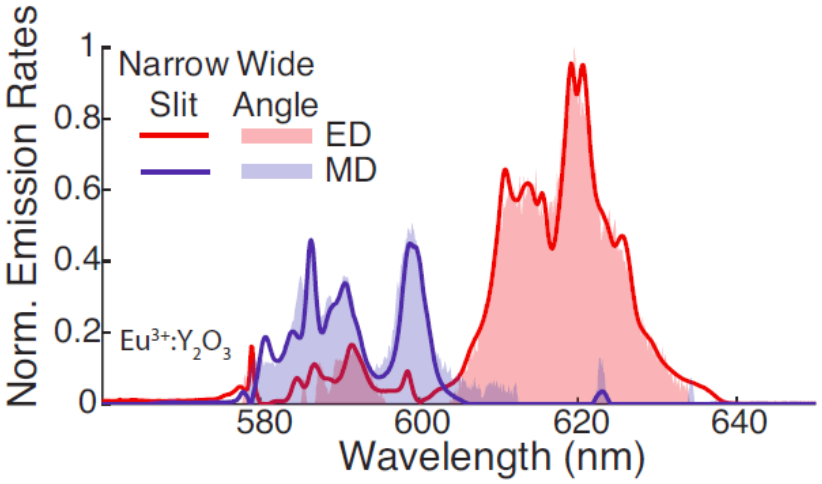
Wide-Angle Energy-Momentum Spectroscopy

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:

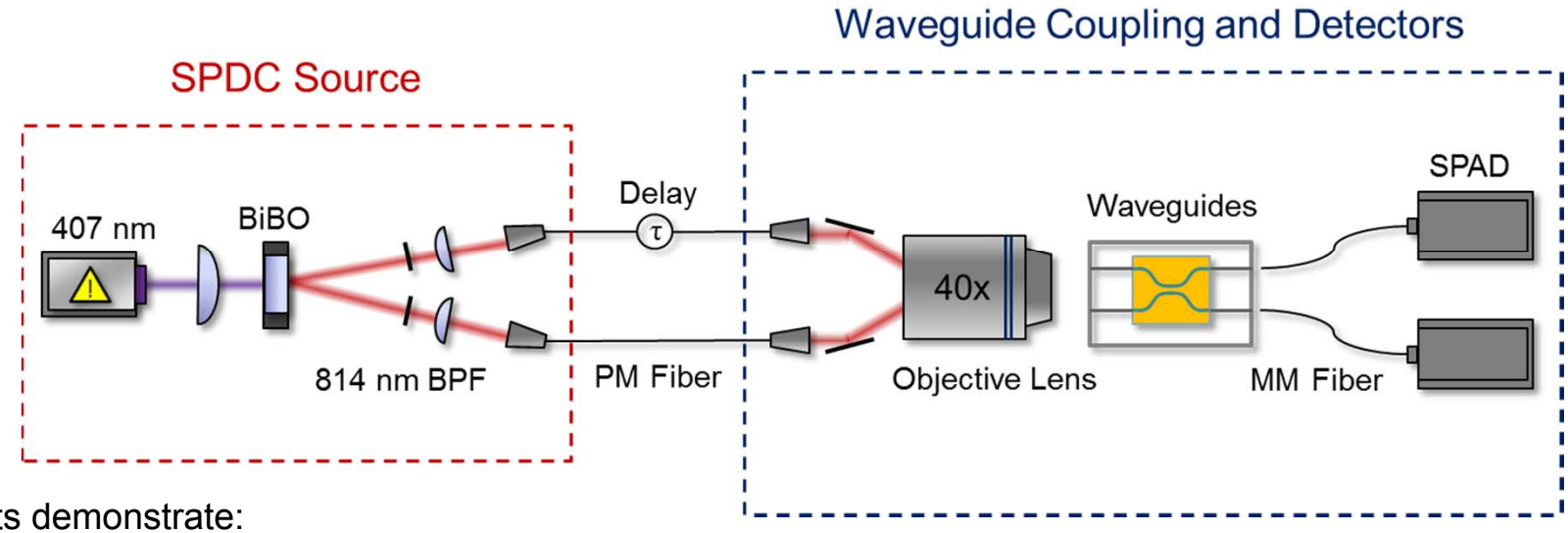
- Simultaneous measurement of the polarized radiation patterns at every wavelength within the measurement domain.
- Improved optical throughput by orders of magnitude without sacrificing spectral resolution.
- Determination of contributions to emission/scattering in any system with well defined basis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



Dodson, Kurvits, Li and Zia, *Optics Letters* **39** (2014), 3927.

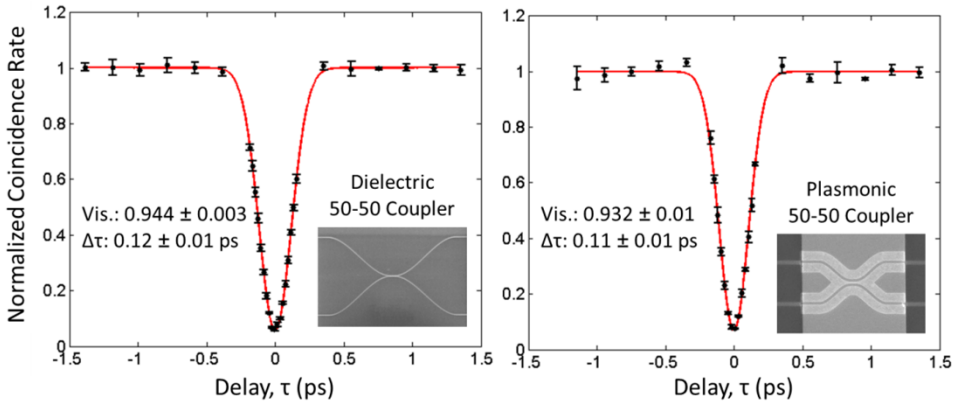
Two-Plasmon Hong-Ou-Mandel Quantum Interference

The Atwater group has developed an on-chip platform for studying Hong-Ou-Mandel style two-plasmon quantum interference (effectively creating plasmonic NOON states).



Results demonstrate:

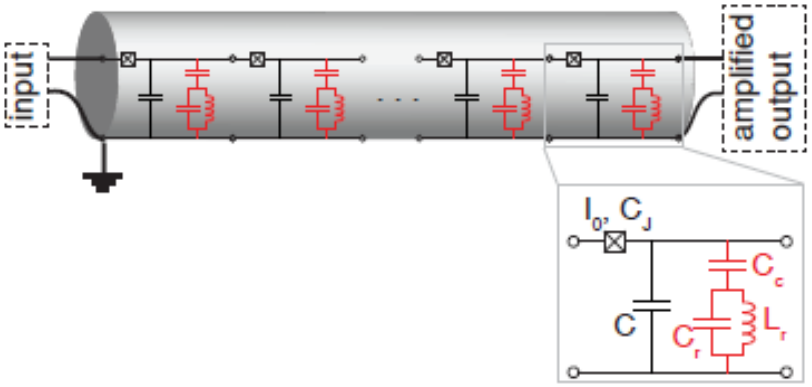
- Surface plasmons exhibit Hong-Ou-Mandel interference without any significant reduction in visibility or coherence.
- Plasmonic quantum interference is identical to the dielectric case.
- Dispersion and dephasing in plasmonic structures does not affect the visibility of interference.

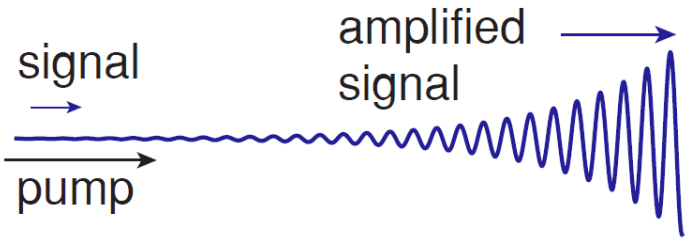


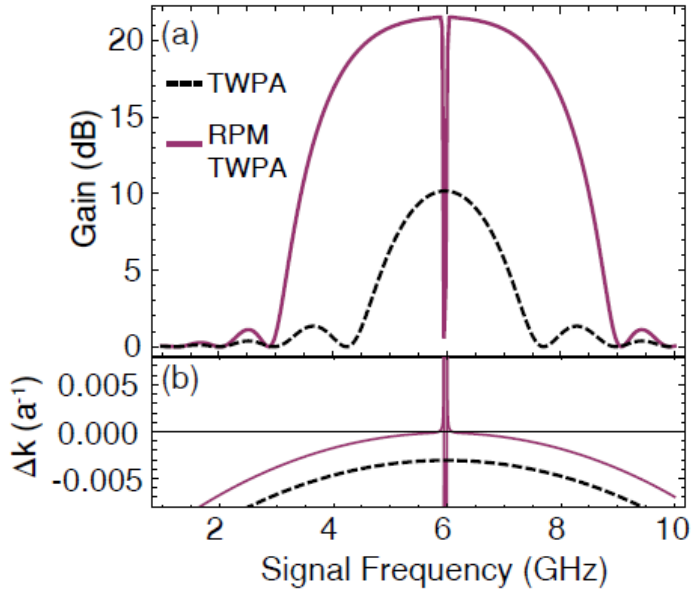
Fakonas, Lee, Kelaita & Atwater, *Nature Photonics* 8, 317–320 (2014)

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)

O'Brien, Macklin, Siddiqi & Zhang. *arXiv*:1406.2346 (2014)

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 retrival 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**

Team Output: 22 Publications in leading scientific journals

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

Brar *et al.*, "Highly Confined Tunable Mid-Infrared Plasmonics in Graphene Nanoresonators", *Nano Lett.* 13 (2013), 2541.

Brar *et al.*, "Hybrid Surface-Phonon-Plasmon Polariton Modes in Graphene/Monolayer h-BN Heterostructures", *Nano Lett.* 14 (2014), 3876.

Cang *et al*., "Giant Suppression of Photobleaching for Single Molecule Detection via the Purcell Effect", *Nano Lett.* 13 (2013), 5949.

Cha *et al.*, "Two-Dimensional Chalcogenide Nanoplates as Tunable Metamaterials via Chemical Intercalation", *Nano Lett.* 13 (2013), 5913.

Chen *et al*., "Versatile Three-Dimensional Virus-Based Template for Dye-Sensitized Solar Cells with Improved Electron Transport and Light Harvesting", *ACS Nano* 7 (2013), 6563.

Dang *et al.*, "Tunable Localized Surface Plasmon-Enabled Broadband Light-Harvesting Enhancement for High-Efficiency Panchromatic Dye-Sensitized Solar Cells", *Nano Lett.* 13 (2013), 637.

Dodson *et al.*, "Wide-angle energy-momentum spectroscopy", *Opt. Lett.* 39 (2014), 3927.

Fakonas *et al*., "Two-plasmon quantum interference", *Nature Photon.* 8 (2014), 317.

Fung *et al.*, "Electron-photon scattering mediated by localized plasmons: A quantitative analysis by eigen-response theory", *Phys. Rev.* B 89 (2014), 045408.

Jha *et al.*, "Quantum coherence-assisted propagation of surface plasmon polaritons", *Appl. Phys. Lett.* 102 (2013), 091111.

Jin and Fang, "Plasmonic angular momentum on metal-dielectric nano-wedges in a sectorial indefinite metamaterial", *Opt. Express* 21 (2013), 28344.

Jin *et al.*, "Terahertz plasmonics in ferroelectric-gated graphene", *Appl. Phys. Lett.* 102 (2013), 201118.

Karaveli *et al*., "Time-Resolved Energy-Momentum Spectroscopy of Electric and Magnetic Dipole Transitions in Cr^{3+}:MgO", *ACS Nano* 7 (2013), 7165.

Kumar *et al.*, "Photon emission rate engineering using graphene nanodisc cavities", *Opt. Express* 22 (2014), 6400.

Maas *et al.*, "Experimental realization of an epsilon-near-zero metamaterial at visible wavelengths", *Nature Photon*. 7 (2013), 907.

Team Output: 22 Publications in leading scientific journals

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Rephaeli and Fan, “Dissipation in few-photon waveguide transport”, *Photon. Research* 1 (2013), 110.

Shi and Fan, “Two-photon transport through a waveguide coupling to a whispering-gallery resonator containing an atom and photon-blockade effect”, *Phys. Rev. A* 87 (2013), 063818.

Silveirinha and Engheta, “Giant nonlinearity in zero-gap semiconductor superlattices”, *Phys. Rev. B* 89 (2014), 085205.

Silveirinha and Engheta, “Spatial Delocalization and Perfect Tunneling of Matter Waves: Electron Perfect Lens”, *Phys. Rev. Lett.* 110 (2013), 213902.

Sokhoyan and Atwater, “Quantum optical properties of a dipole emitter coupled to an “-near-zero nanoscale waveguide”, *Opt. Express* 21 (2013), 32279.

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

Xu *et al.*, “Analytic Properties of Two-Photon Scattering Matrix in Integrated Quantum Systems Determined by the Cluster Decomposition Principle”, *Phys. Rev. Lett.* 111 (2013), 223602.

All Publication Information available at www.QuantumMetaphotonics.com

Including 6 Additional arXiv Preprints under review or in press.

Babinec et al., “A Light-Matter Interface based on a Single InAs/GaAs Quantum Dot in a Nanometallic Cavity”, arXiv:1406.7050.

Jang et al., “Tunable Large Resonant Absorption in a Mid-IR Graphene Salisbury Screen”, arXiv:1312.6463.

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

Lee et al., “Optical Torque from Enhanced Scattering by Multipolar Plasmonic Resonance”, arXiv:1405.0239.

O'Brien et al., “Resonantly phase-matched Josephson junction traveling wave parametric amplifier”, arXiv:1406.2346.

Xu et al., “Near-field Holographic Retrieval of an Isolated Subwavelength Hole in a Thin Metallic Film”, arXiv:1404.0441.

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

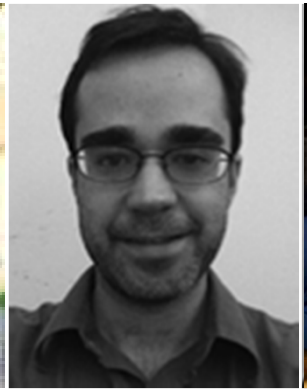
- Nature Photonics News & Views feature on graphene nanoresonators from Atwater group
- Materials Today podcast with Rashid Zia on energy-momentum spectroscopy

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.

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