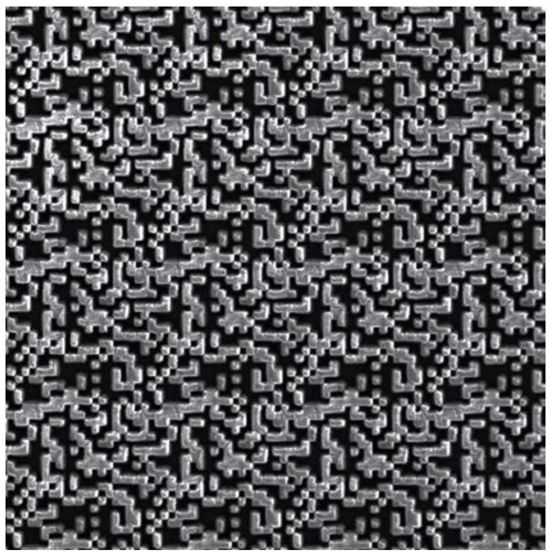
IRG: Manipulating Light with Materials

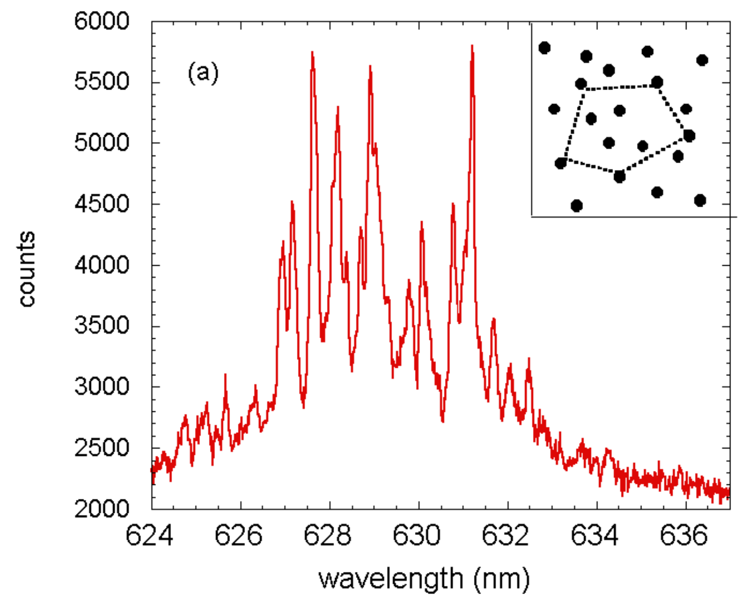
A cross-disciplinary effort involving the Departments of

Physics: Li, Pesin, Raikh, Vardeny
Mathematics: Golden, Guevara-Vasquez, Milton
Electrical and Computer Engineering: Menon
Mechanical Engineering: Park

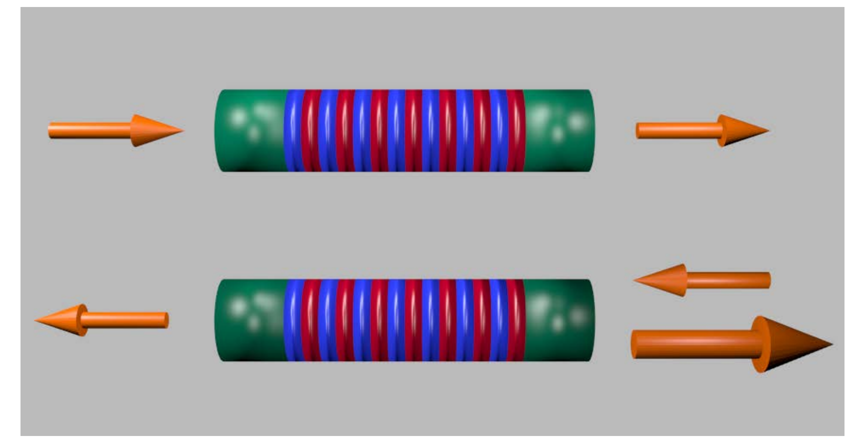
Theory, computation, design and fabrication of novel materials and devices to manipulate light for exciting applications.



Digital MetaMaterials (DMMs) enhancing photonic integration



Random Lasers (RLs) imaging cancer



Parity-Time Symmetry (PTS) unidirectional optics

Cutting edge mathematics on the interactions of electromagnetic waves with materials provides the foundation.

IRG Director: Ken Golden

FRG1: Digital Metamaterials **Group Leader:** Rajesh Menon

Graeme Milton, Fernando Guevara-Vasquez, Kay Park, Ken Golden

FRG2: Random Lasers **Group Leader:** Misha Raikh

Valy Vardeny, Dima Pesin, Sarah Li, F. Guevara-Vasquez, Ken Golden

FRG3: P-T Symmetry **Group Leader:** Valy Vardeny

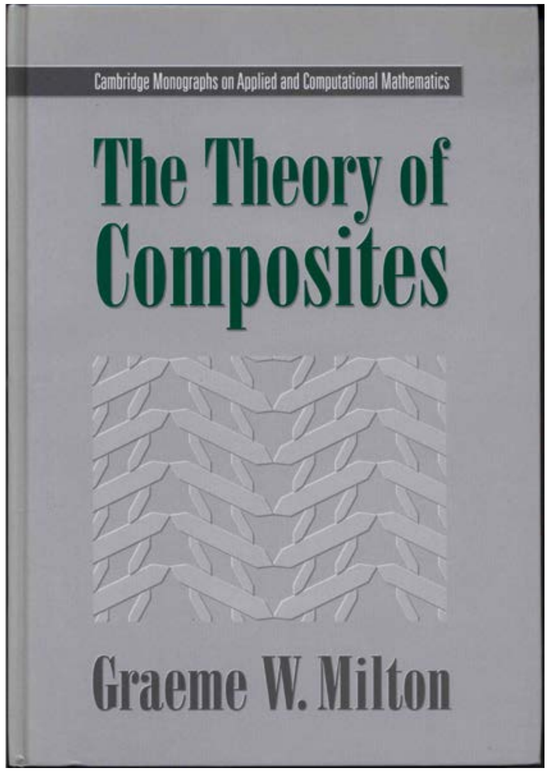
Misha Raikh, Sarah Li, Dima Pesin (and external participants)

Why fund this IRG?

- Integrated photonics can leapfrog power density and bandwidth limitations of nanoelectronics -- major risks to a trillion-dollar semiconductor industry.
- Fundamental breakthroughs in integration density to enable integrated metamaterial-based photonics.
- Rigorous techniques to tailor a material to optimize laser performance.
- Strategy and realization of imaging cancerous tumors with random lasers.
- Create novel optical devices exploiting the balance of gain and loss in PT symmetric structures.
- Explore and implement PT symmetry for spin waves (magnonics).
- Advance the mathematics of designing materials to control wave behavior, exploiting the interplay between theorists and experimentalists in the group.

What makes this IRG unique?

The infusion of **rigorous mathematics** of composite and structured materials as the platform upon which we will design and optimize complex media and devices to control optical behavior.



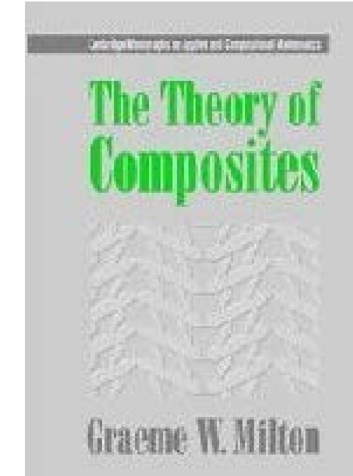
The definitive text in the field.

IRG Research and Engineering Objectives

- Create fundamental theory, explore the potential, and elucidate the limitations of digital metamaterials.
- Design and fabricate DMMs; realize DMM-based nanophotonic devices with enhanced integration density; explore use of chiral materials.
- Develop theory of spatially separated gain and loss in random lasers; design microstructures to achieve optimal performance.
- Explore optical gain and laser action of media with chiral chromophores or mirror-like scatterers.
- Develop a strategy for RL imaging of cancerous tissue.
- Design optimal materials to balance optical gain and loss in PTS devices.
- Fabricate and study tri-layer ferromagnetic structures to realize PT symmetry in spin waves; cross-pollinate from optics to magnonics.

High impact publications and research results

- Book
  - *The Theory of Composites* (GM): cited more than 1800 times
- Journal Publications
  - Founding paper on cloaking (GM): founding paper on random lasers (VV, MR)
  - Most downloaded paper in OSA journals in 2007 (GM): >13,000 times
  - Published in *Nature Photonics*, *PRL* (2), *Science*, and *Optica* - pioneering DMM works (RM)
  - Published in *PRL* and *APL* (3) on cloaking and ultrasound control of particles (FG-V)
  - Published in *Nano Letters* and 10 other journals for tip-based nano-manufacturing (KP)
  - Published in *Nature Physics*, *PRL* (2), *PRB* (5) on random lasers (VV, MR)
  - Published in *Nature, Science, Nature Physics* (2), *PRL* (4), *Optics Letters* (3) on photo-excitations and laser action in organic and hybrid organic-inorganic perovskites (VV)
  - Published in *Nature, Science, Nature Materials* (2), *PRL* (2), *Nature Comm*. on spintronics (VV)
  - Published in *Science*, *PRL* (3), *PRSA* (2), *Geophys. Res. Lett., Nature Geophys*. on composites (KG)
- Patents / Commercialization
  - 15 patents and 3 spin-off companies in photonics (RM)



Core Capabilities of the IRG Group

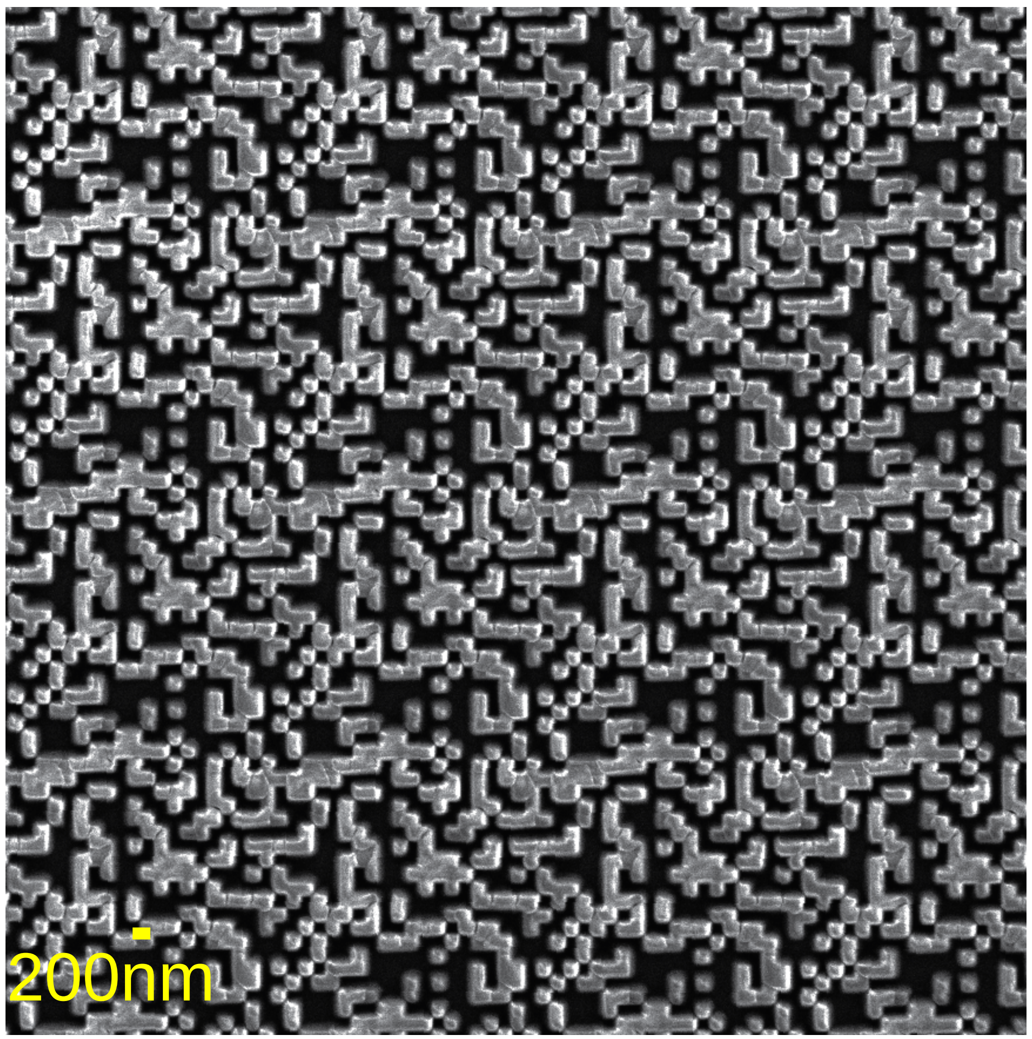
Theoretical and Computational

- Numerical tools using the Amazon cloud for large scale design of nanophotonic devices.
- Novel integral representations and variational principles for the response of devices; theoretical and numerical expertise in cloaking.
- Numerical methods for the optimal design of device components.
- Extensive mathematical and numerical expertise in modeling the effective properties of multiscale composite materials.
- Extensive theoretical expertise in lasers and condensed matter.

Core Capabilities *Experimental and Fabricational*

- **Nanofabrication facility**, including focused-ion-beam lithography, scanning-electron-beam lithography (MRSEC, USTAR), and tip-based nanolithography.
- **Custom experimental systems** to characterize integrated DMM devices.
- **Random laser action:** fs pump/probe; high power ps and ns pulses.
- **Materials:** π-conjugated polymers, hybrid organic-inorganic perovskites, III-V and II-VI quantum dots.
- **MRSEC (USTAR) device fabrication facility:** two glove-boxes, high vacuum evaporators, spin-cast, etc.
- **Magnetic PL research instrumentation:** 7 Tesla cryostat capable of 2K.
- **Dedicated chemist** synthesizing organic and hybrid organic-inorganic materials.
- **Magnetic research instrumentation:** tunable FMR, inverse spin Hall effect, optically-detected magnetic resonance, Brillouin light scattering spectrometer.
- **Magneto-optic spectroscopy:** Sagnac interferometer, 20 nano-rad angular resolution.

FRG1: Digital Metamaterials (DMMs) for enhancing photonic integration



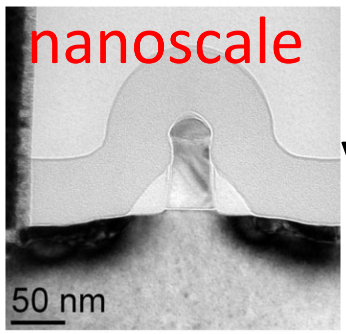
Participants: Menon, *FRG Leader*; Milton, Guevara-Vasquez, Golden, Park. 1 postdoc, 2 grad students.

Example of a DMM polarizer.
Shen, *et al*, *Optica* 1(5), 356 (2014)

Why DMMs?

- **Leapfrog power & bandwidth limitations of nanoelectronics**
- **Create fundamental breakthroughs in chiral & non-chiral DMMs**

Transistor (electronic switch)



vs

Modulator (photonic switch)

macroscale

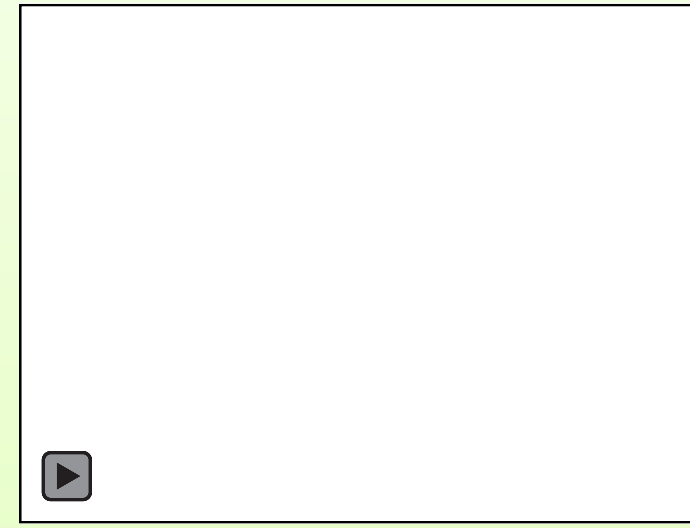
Fundamental problem:
De broglie wavelength of electron is **>100X** smaller than that of an IR photon!

if addressed, will enable

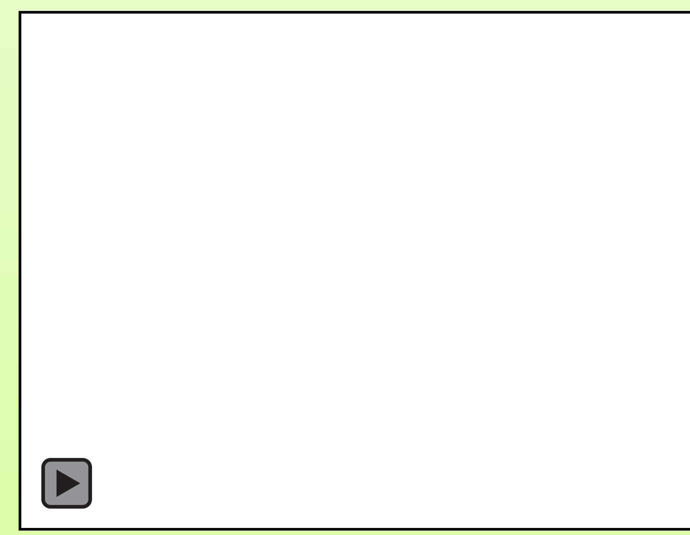
Ultra-high integration of photonics with digital metamaterials

solved by

World's smallest polarization beamsplitter



Cloaking to increase integration density



Shen and *et al.*, **Nature Photonics** 9, 378 (2015).

Research Objectives

By combining **theory**, **numerical optimization**, **fabrication** & **experiments**, we will pioneer **chiral and non-chiral DMMs** to drastically enhance the integration density of photonics.

- **Create** the fundamental theory of digital metamaterials.
- **Elucidate** the limits of integration density
- **Design, fabricate, and characterize** digital metamaterials
- **Realize** nanophotonic devices with enhanced integration density
- **Explore** whether periodic arrays of these devices can produce metasurfaces with novel properties

Research Plan Overview

Milton, Guevara-Vasquez (GV), Golden (Math), Menon (ECE), Park (ME)

Theory (Milton, GV, Golden)

Fundamental limits

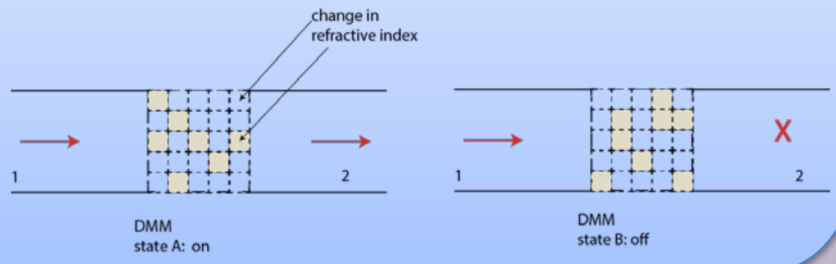
Transient behavior

1. $\nabla \cdot \mathbf{D} = \rho_V$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

Design (GV, Menon)

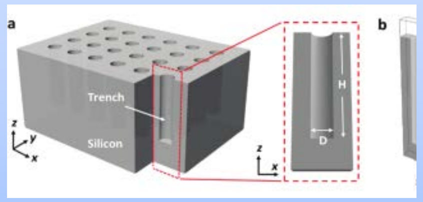
Numerical techniques

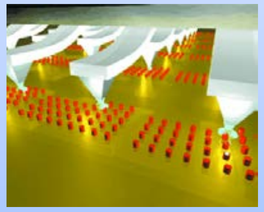
Cloud computing



Fabrication (Menon, Park)

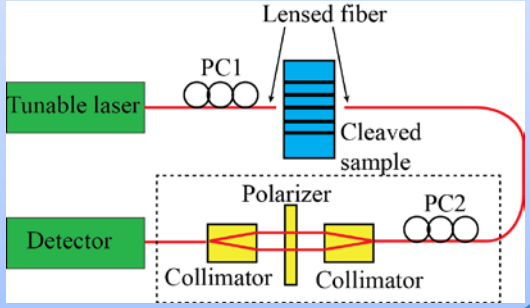
2D, 3D, scalable, cost-effective





Experiments (Menon)

Transient, Quantum



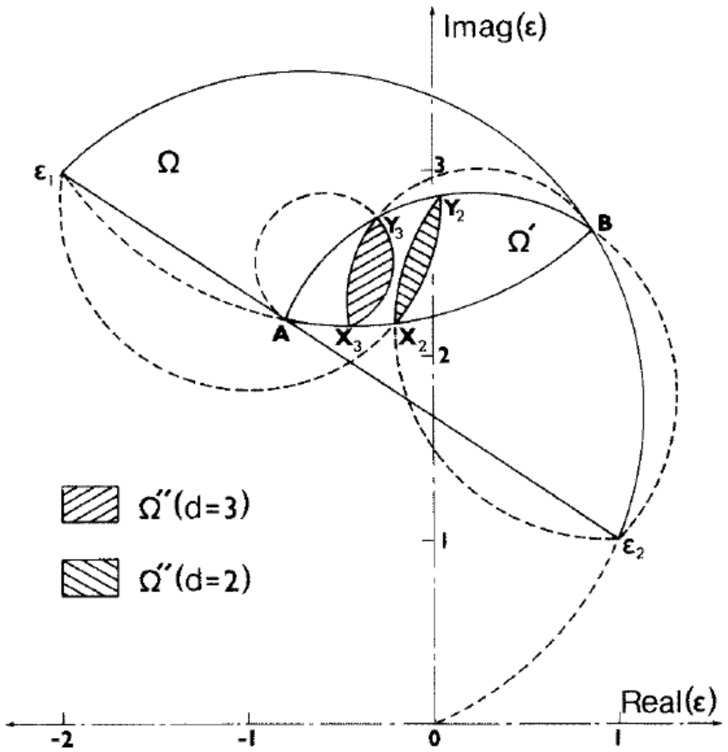
FRG1 Research Plan: Theory

Fundamental questions:

- How do DMMs work?
- Is **<u>interference</u>** from waves going through different channels responsible?
- What are the fundamental limitations of DMMs?

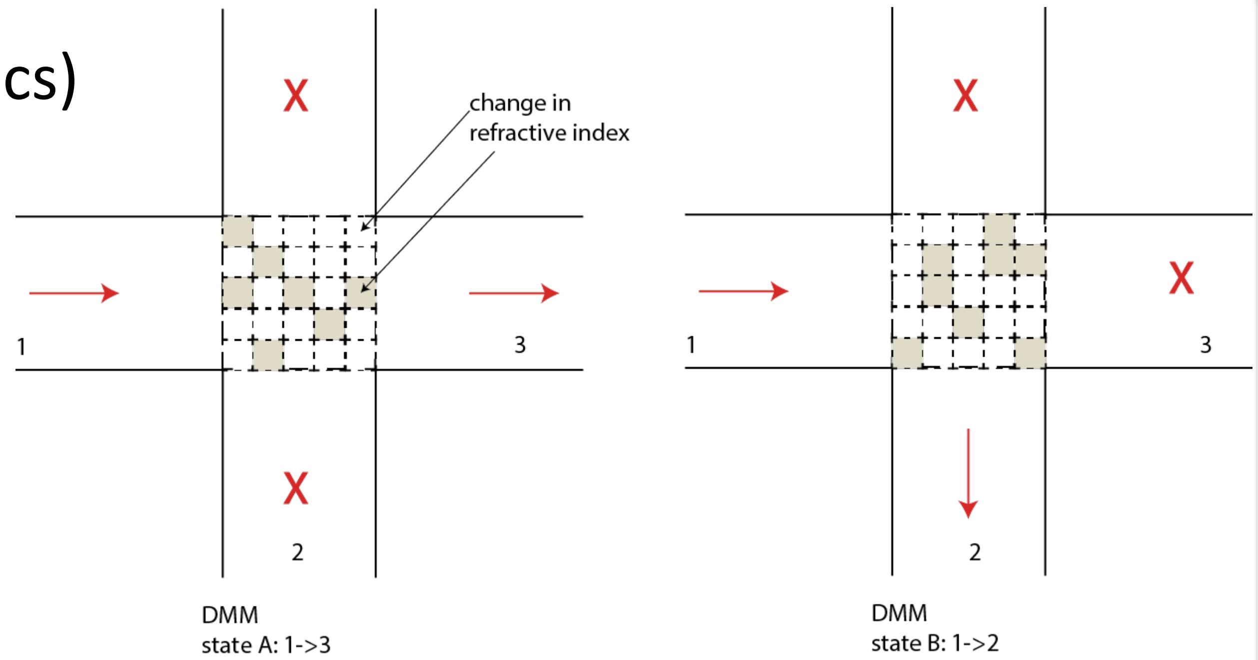
Mathematical approaches for finding limitations:

- For composites the Bergman-Milton bounds limit the possible complex dielectric constant.
- Derived via integral representations or via minimization variational principles [Bergman, Milton, Golden and Papanicolaou, Cherkaev and Gibiansky].
- Similar tools are available for bounding the dynamic electromagnetic response function of bodies [Milton and collaborators].



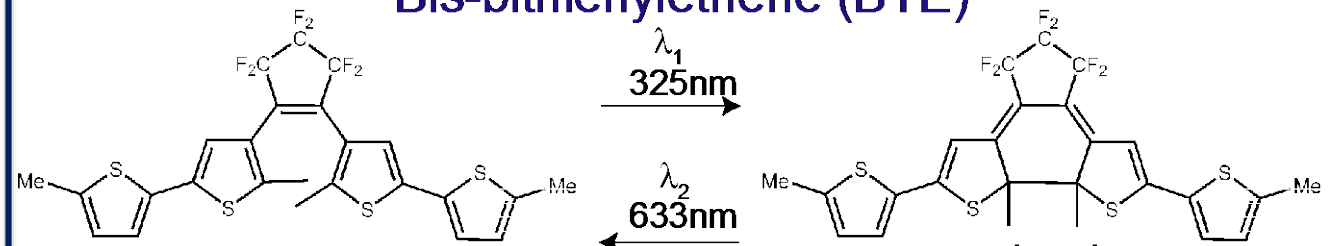
FRG1 Research Plan: Design

Active DMMs: photonic multi-state machines can be modulated by carrier injection (electronics)



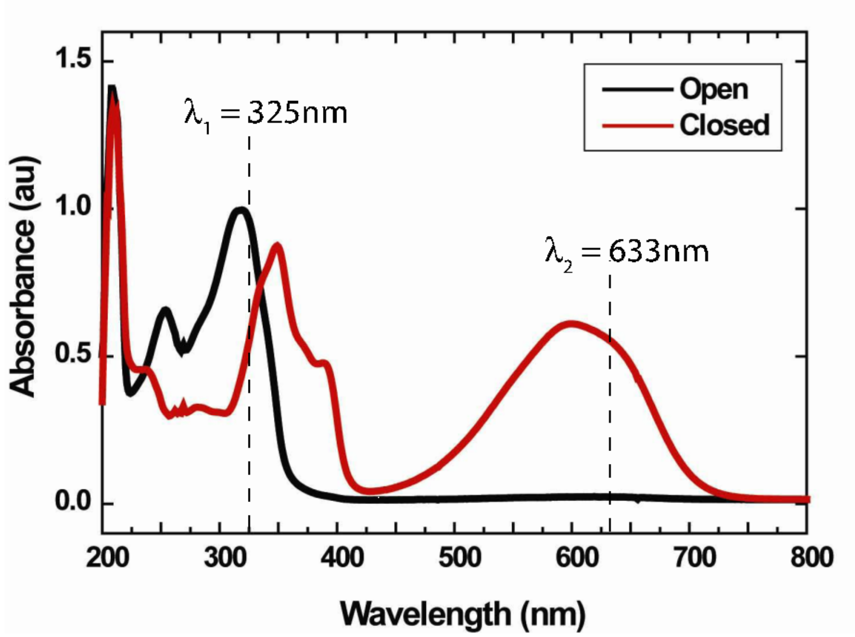
Photochromic molecules of the diarylethene family

Bis-bithienylethene (BTE)



open closed

UV-Vis Spectra



Tsai *et al. Science* 324, 917 (2009)

Alternative modulation with light

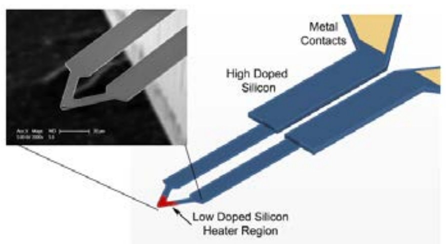
DMMs designed via **optimization** to perform specific tasks within fabrication constraints.

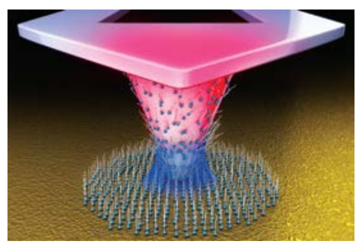
Applications in isolators, modulators, switches, etc.

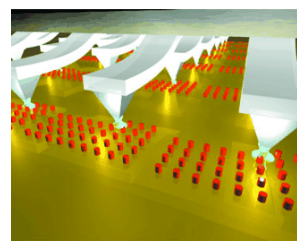
FRG1 Research Plans: Fabrication and Experiment

Fabrication

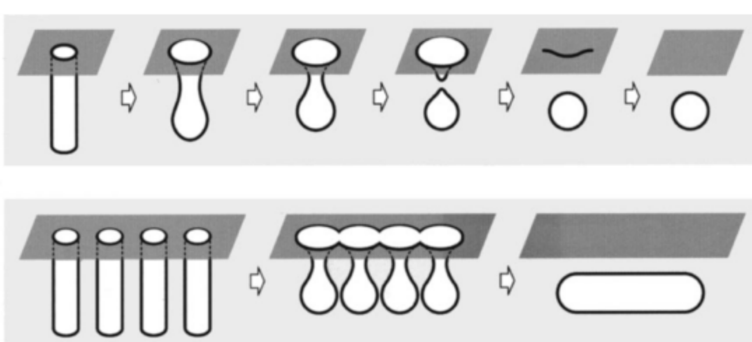
- Tip-Based Nanolithography
  - Pattern 10-nm-order pixels with scanning probe microscopy to fabricate DMMs in the visible range





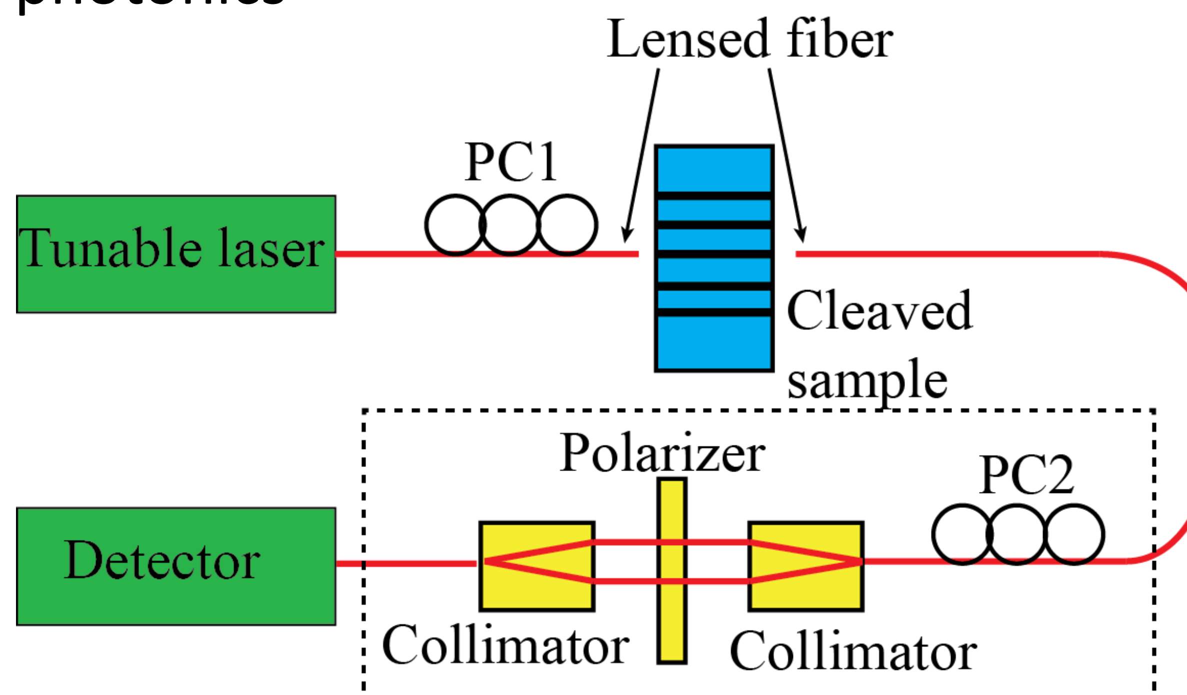


- Silicon-on-Nothing Manufacturing
  - Utilize self-migration of Si atoms at high temperature to fabricate 3D DMMs



Experiments

Custom probe station for integrated photonics



- polarization-sensitive measurements
- transient behavior
- quantum measurements
- chirality-sensitive measurements

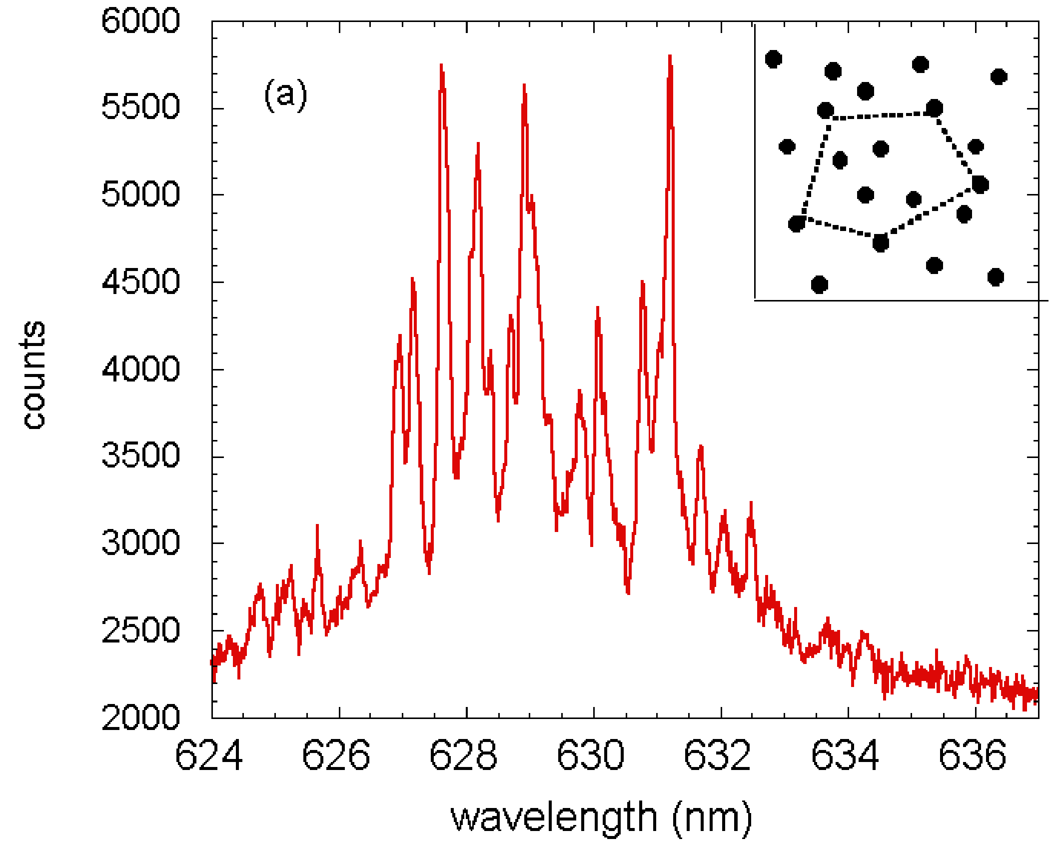
Impact of FRG1

- Discover the underlying mechanisms of digital metamaterial (DMM) devices.
- Significantly reduce the energy requirements of data centers through DMM-based optical inter-connects.
- Discover chiral DMM for potential order of magnitude increases in bandwidth.

FRG2: Wave propagation in complex materials with gain; near-threshold random lasing

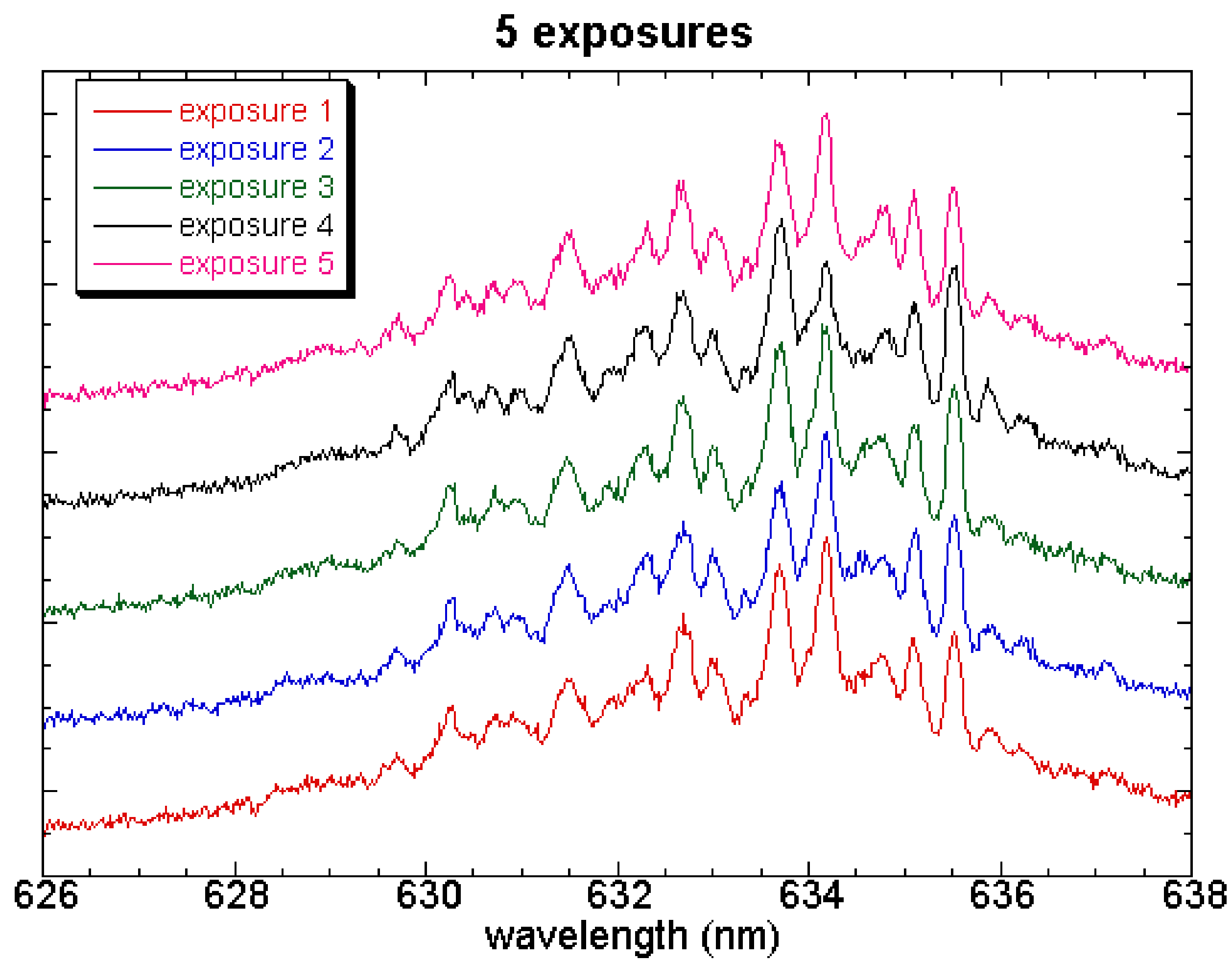
Participants: Raikh, *FRG Leader*; Vardeny, Golden, Pesin, Li. 1 postdoc, 1 grad student; *Collaborator:* Randy Polson, Nanofab.

1. Studies of Random Lasing in Organics



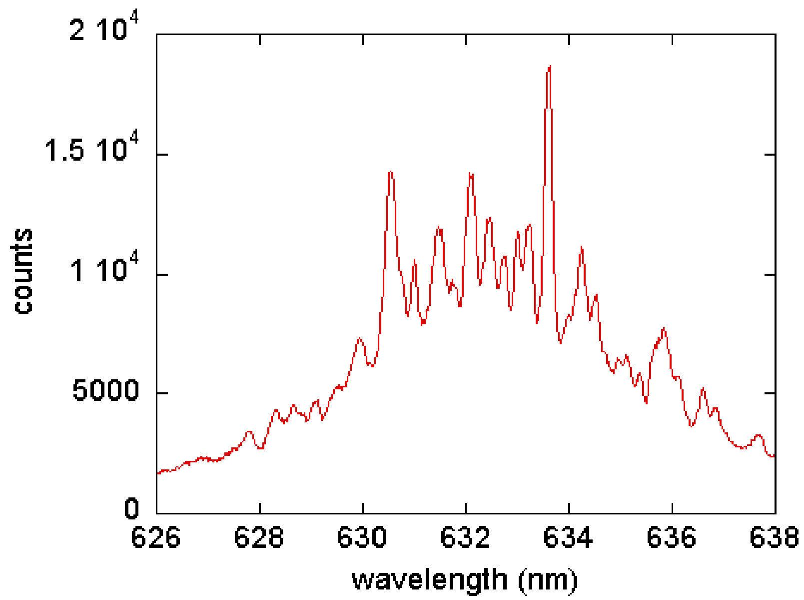
Random lasing in a DOO-PPV film at high excitation intensity;
the narrow lines (<1nm) are coherent radiation due to random resonators

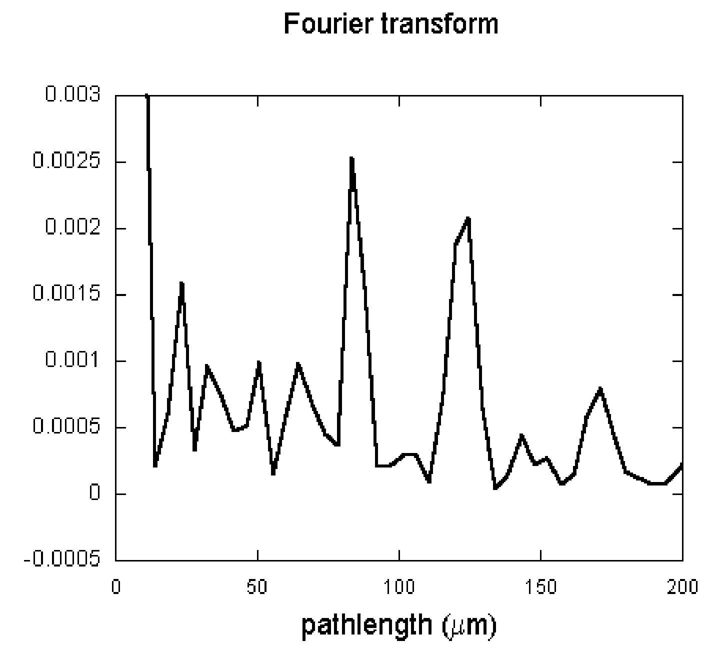
1. Random lasing reproducibility

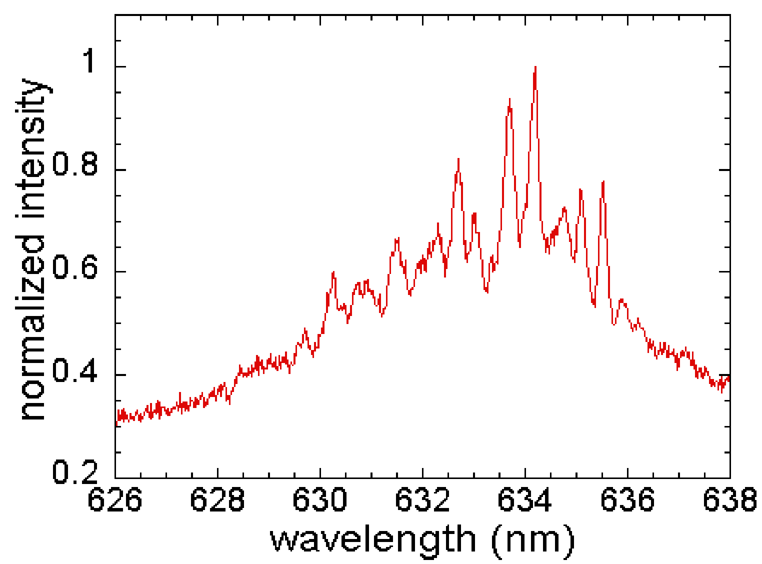


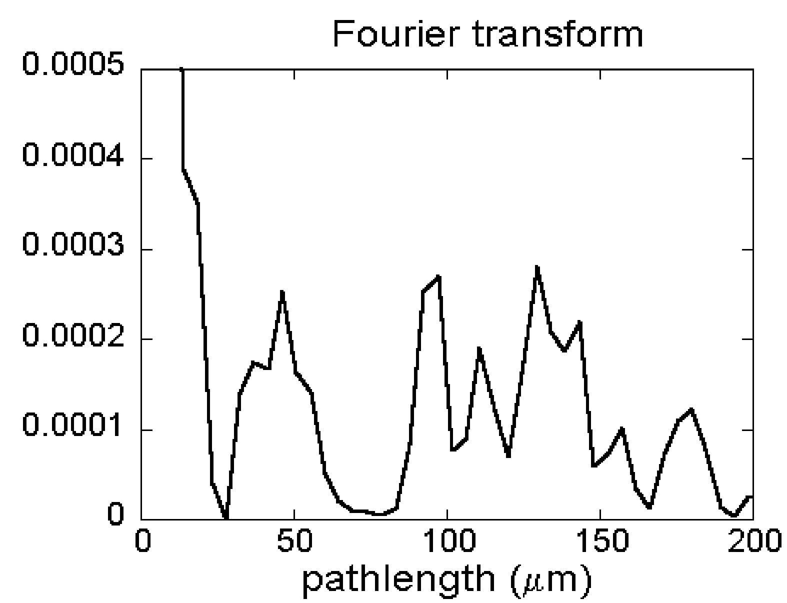
The sharp peaks are completely reproduced

Random Laser; FT spectrum

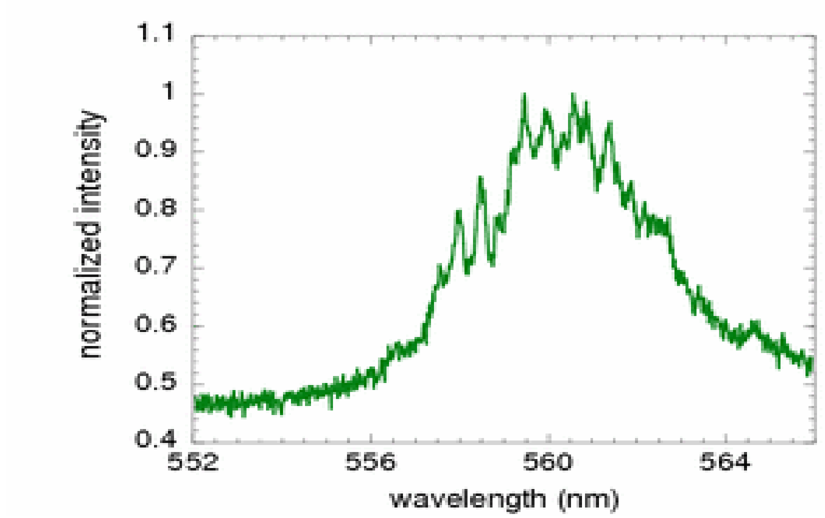


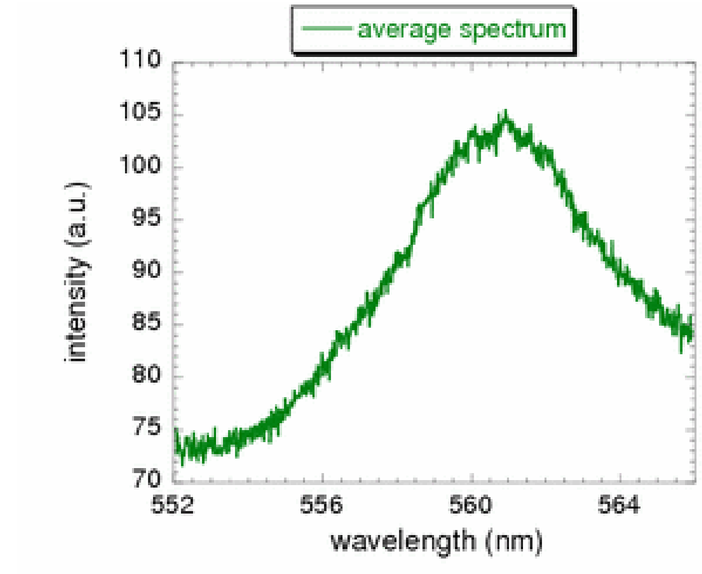


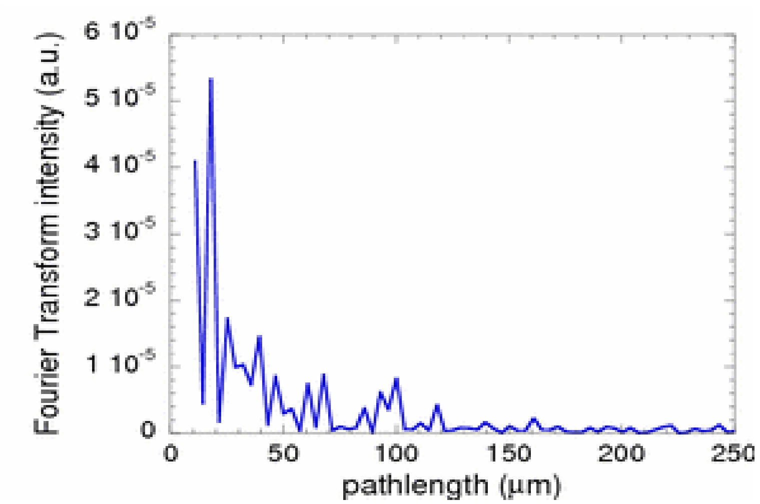


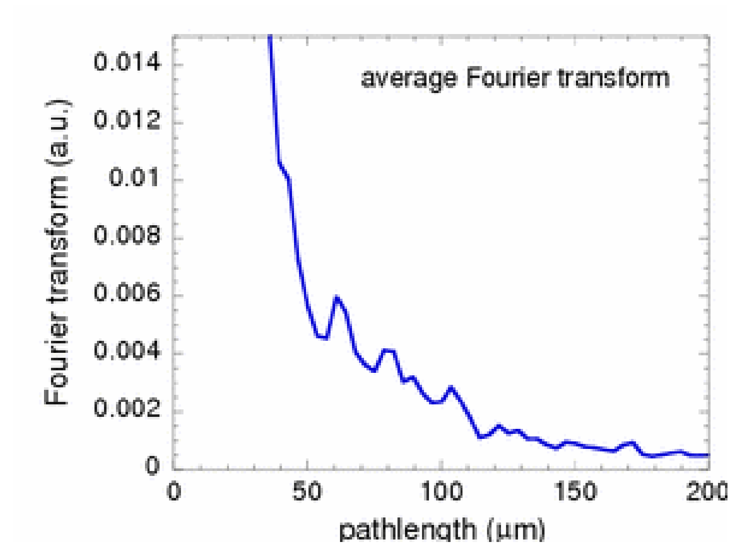


Average Spectrum, Fourier transform

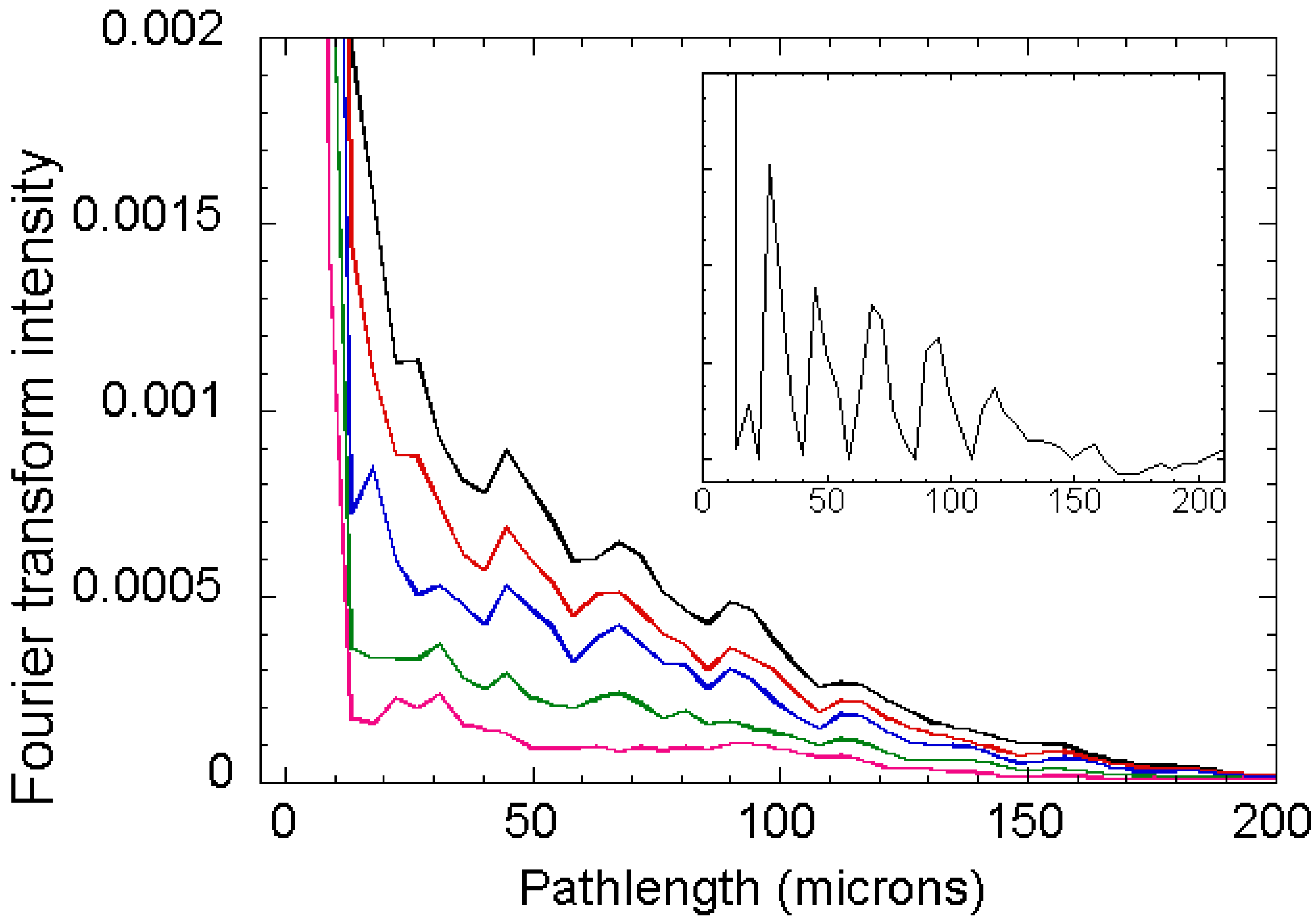








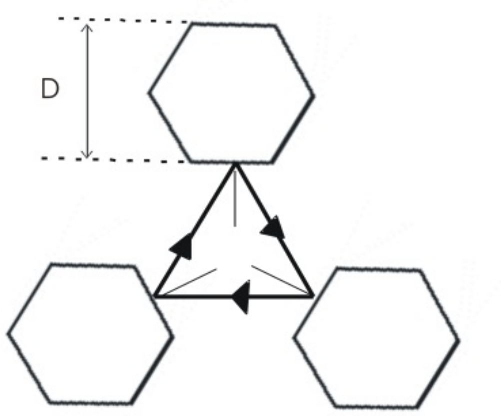
1. Random Lasers; average power Fourier transform build-up



Average Fourier transform of random laser emission spectra revealing the dominant random cavity in the gain medium material

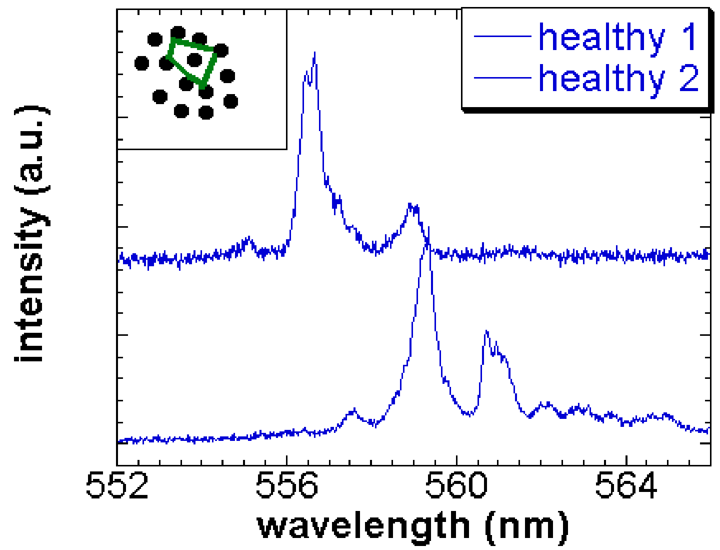
2. Research & Engineering Challenges

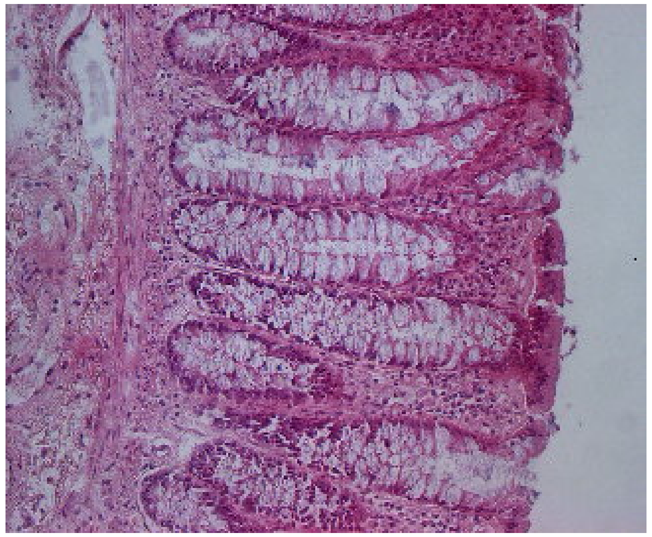
- Study Random Lasing where the optical gain and loss are spatially separated and balanced.
- Explore Random Lasing in materials with chiral optical gain and loss.
- Investigate Random Lasing in materials with optical gain impregnated with ‘mirror-like’ scatterers.
- Seek RL applications in the Health Sciences.



Applications of random lasing in tumors

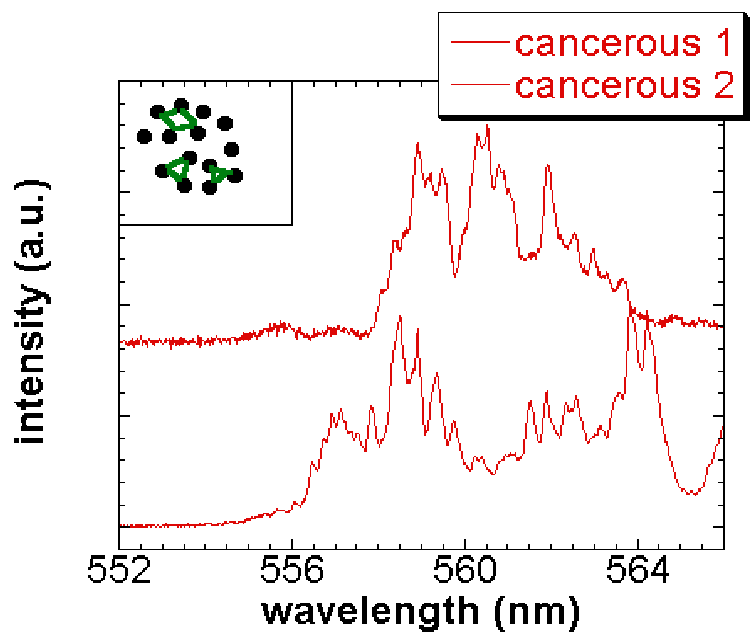
Laser emission spectra **Stock images (colon)**

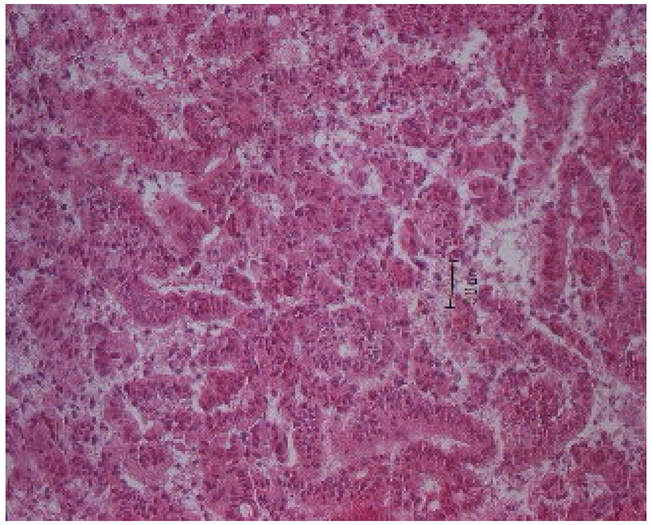




Healthy tissue

Polson and Vardeny, Appl. Phys. Lett.





cancerous

Malignant tumors show many more sharp peaks

3. Research Plan

- Fabricate novel optical materials with spatially separated gain and loss; demonstrate RL threshold and its dependences on avg gain and sample size.
- Fabricate novel chiral materials having optical gain; chiral molecules or hybrid perovskites at high magnetic field.
- Study RL in chiral materials.
- Fabricate ‘mirror-like’ scatterers in the visible spectral range, study RL thresholds, spectra and emissions.
- Explore RL in cancer tissues, and design ‘RL tomography’ of cancer; commercialization.

Impact of FRG2

- Control Random Lasing using artificial scatterers
- Design Random Laser devices based on chiral chromophores
- Find commercial applications for ‘RL imaging’ in the Health Sciences and Biomedical Engineering

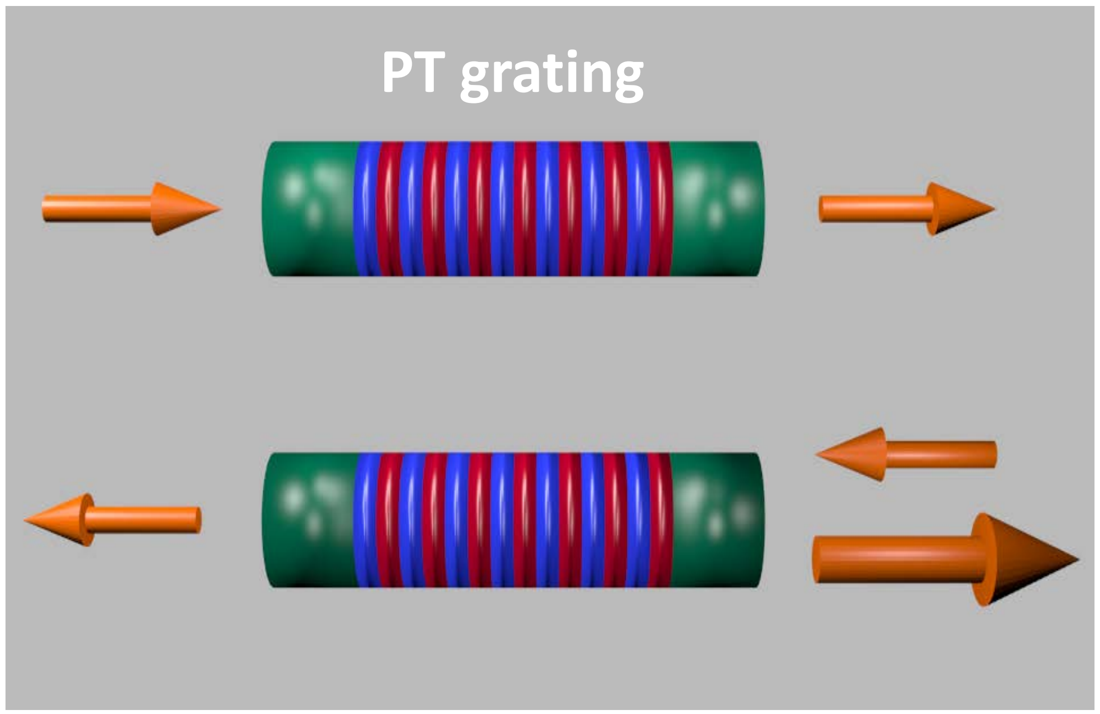
FRG3

Parity-Time Symmetry; Materials and Devices

Participants: Valy Vardeny, FRG Leader; Sara Li, Dima Pesin, Misha Raikh. ***External***: T. Kottos (Wesleyan), B. Shapiro (Technion), V.V. Tsukruk (GaTech). 1 postdoc, 2 grad students

$\mathcal{PT}$-symmetric in optical structures: unidirectional invisibility

Optical Isolator



Red=gain; blue=loss

Nature Materials, February 2013

- Light entering the structure from the ***left does not*** experience reflection.
- In contrast, light incident from the ***right*** experiences ***high reflectivity***.

PT Symmetry in Optics; interplay between gain and loss

Paraxial wave equation ⟷ **PT Schrödinger equation**

$$i\frac{\partial E}{\partial z}+\frac{1}{2k}\frac{\partial^2 E}{\partial x^2}+k_0 n(x)E=0 \quad \longleftrightarrow \quad i\hbar\frac{\partial \psi}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2}+V(x)\psi$$

Propagation constants ⟷ **Energy eigenvalues**

$n_R(x)=n_R(-x)$ Index profile ⟷ $V_R(x)=V_R(-x)$

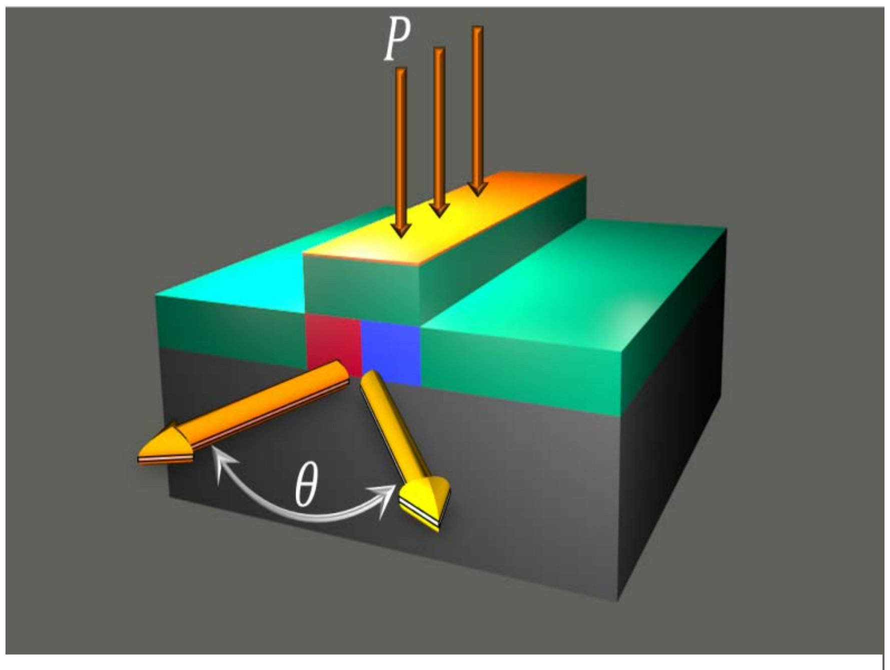
$n_I(x)=-n_I(-x)$ Gain - loss profile ⟷ $V_I(x)=-V_I(-x)$

Complex refractive index: $n(x)=n_R(x)+in_I(x)$

PT symmetry requires that *n*(*x*)=*n(-*x*); i.e. loss=gain**

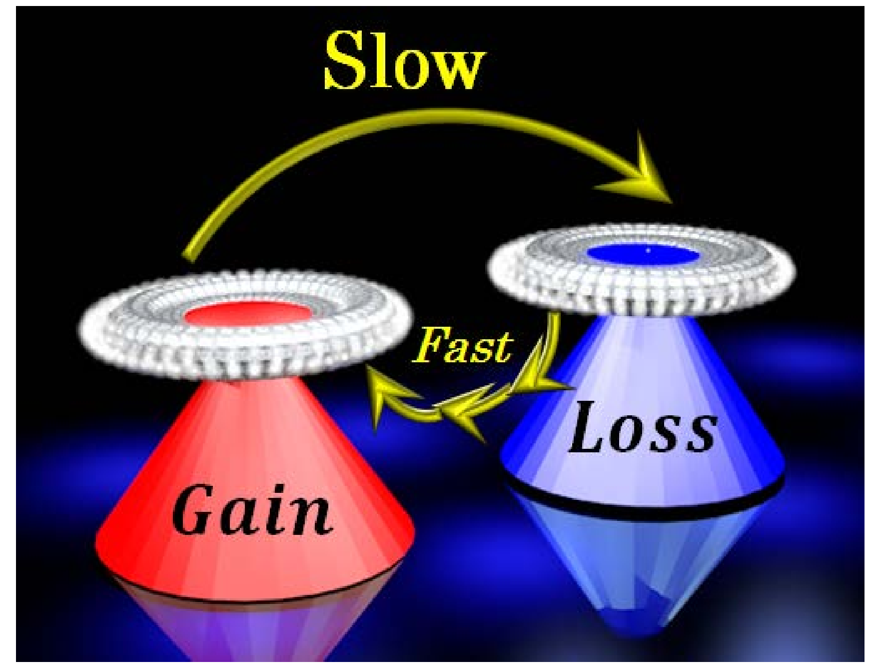
Examples of planned $\mathcal{PT}$ symmetry optical devices

PT-deflector



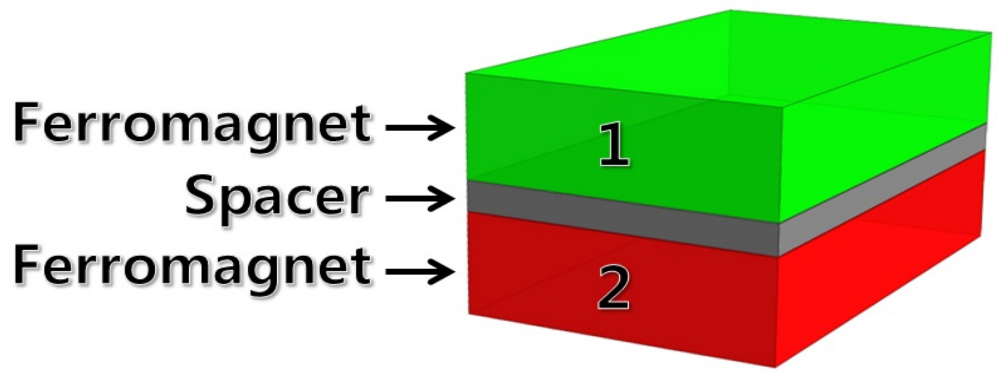
Deflection depends on the contrast between gain and loss

Asymmetric energy exchange



Energy transfer rate depends on the contrast between gain and loss

PT-symmetry in Magnetics; two coupled FM layers



T. Kottos and B. Shapiro; 2015

$$E_{coup} = -K\vec{M}_1 \cdot \vec{M}_2; \quad (K > 0)$$

$$\frac{d\vec{M}_1}{dt} = -\gamma \vec{M}_1 \times \vec{H}_1 - \gamma K \vec{M}_1 \times \vec{M}_2 + \frac{\alpha}{\|\vec{M}_1\|} \vec{M}_1 \times \frac{d\vec{M}_1}{dt}$$

LLG equation

$$\frac{d\vec{M}_2}{dt} = -\gamma \vec{M}_2 \times \vec{H}_2 - \gamma K \vec{M}_2 \times \vec{M}_1 - \frac{\alpha}{\|\vec{M}_2\|} \vec{M}_2 \times \frac{d\vec{M}_2}{dt}$$

P

1 → 2
2 → 1

Apply the Parity Operator: $1 \leftrightarrow 2$

$$\frac{d\vec{M}_1}{dt} = -\gamma \vec{M}_1 \times \vec{H}_1 - \gamma K \vec{M}_1 \times \vec{M}_2 - \frac{\alpha}{\|\vec{M}_1\|} \vec{M}_1 \times \frac{d\vec{M}_1}{dt}$$

T

t → -t
A → -A

Apply the Time Operator: $t \to -t;\ \vec{A} \to -\vec{A}$

$$\frac{d\vec{M}_1}{dt} = -\gamma \vec{M}_1 \times \vec{H}_1 - \gamma K \vec{M}_1 \times \vec{M}_2 + \frac{\alpha}{\|\vec{M}_1\|} \vec{M}_1 \times \frac{d\vec{M}_1}{dt}$$

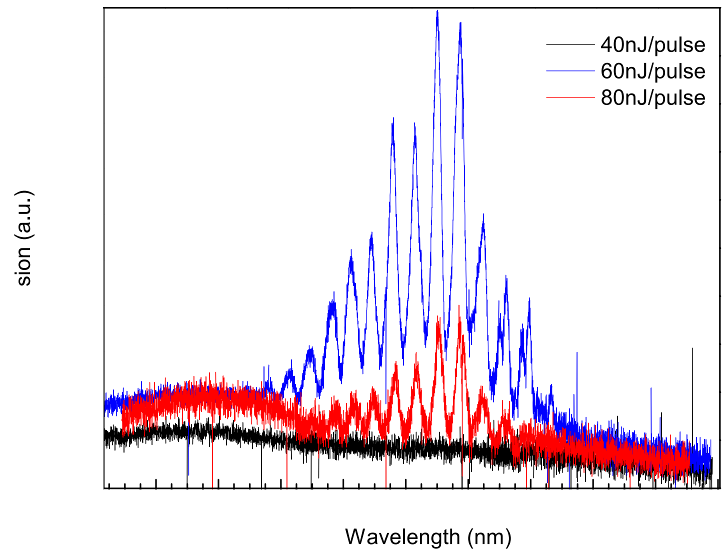
Questions and Challenges for FRG3

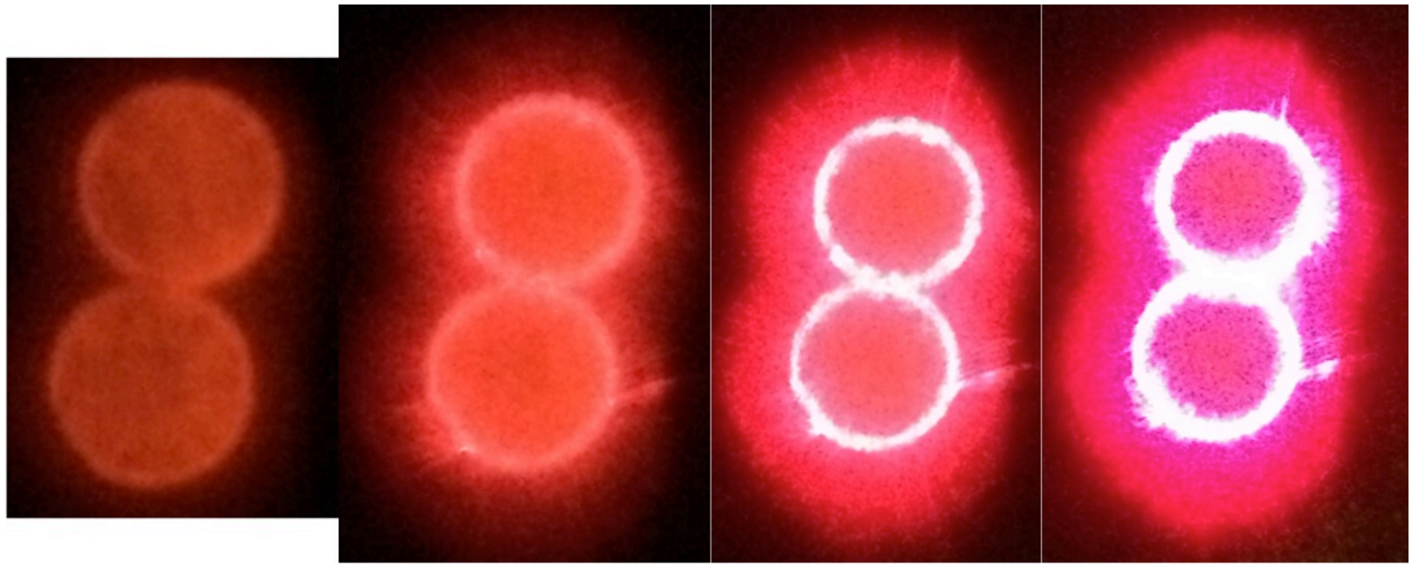
- Find the best material for optical gain and optical loss interplay
- What is the role of chirality in PT symmetry?
- Prove experimentally the existence of PT in Magnetism, and investigate what is meant by gain and loss

Research & Engineering Objectives

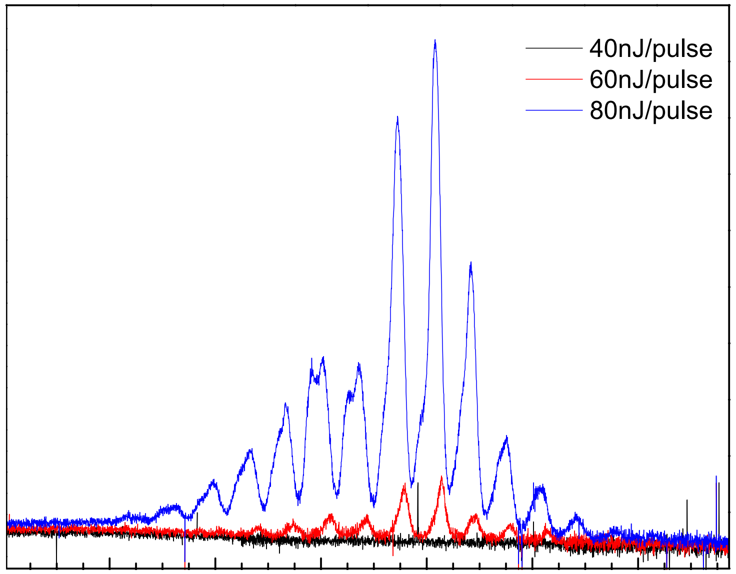
- Fabricate novel optical devices based on PT symmetry
- Study magnetic trilayers of FM1/NM/FM2
- Fabricate novel devices based on magnetic PT symmetry

Pumping microdisk pair; optical PT symmetry

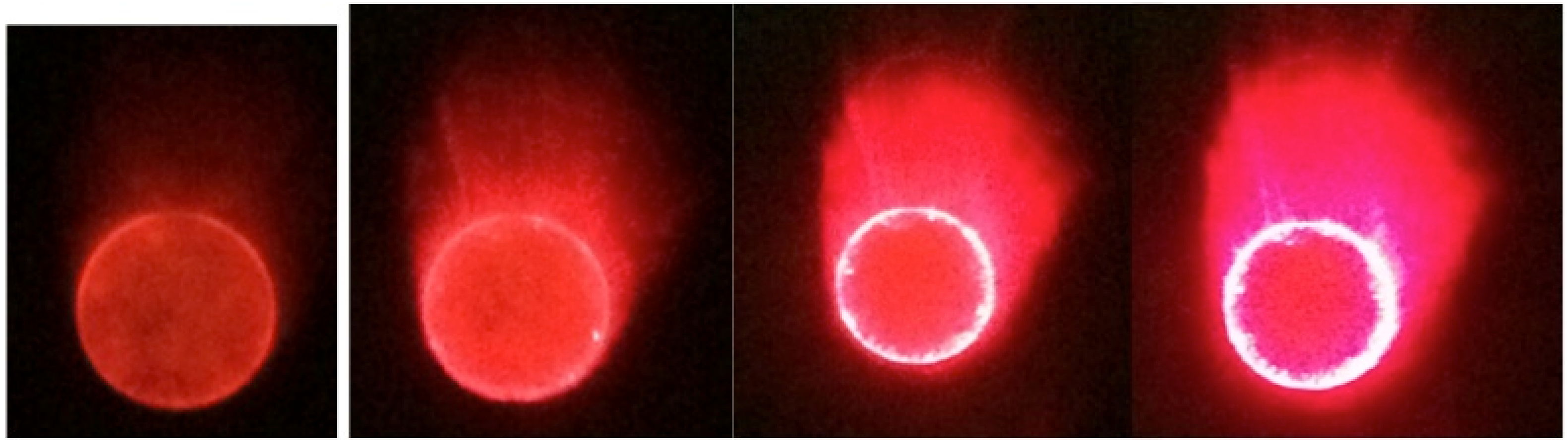




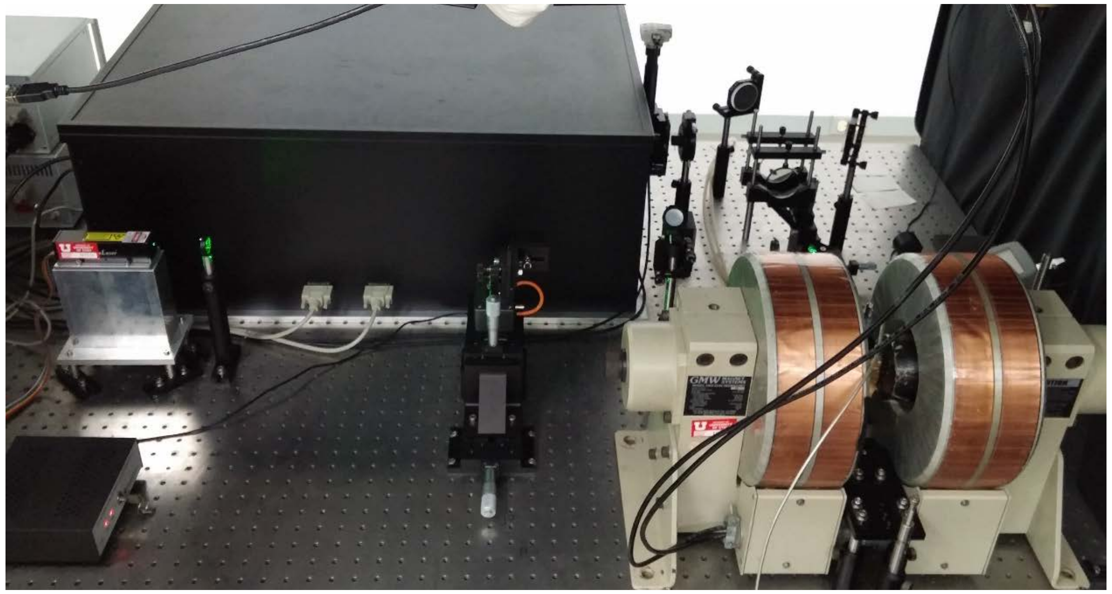
'Mode-splitting'

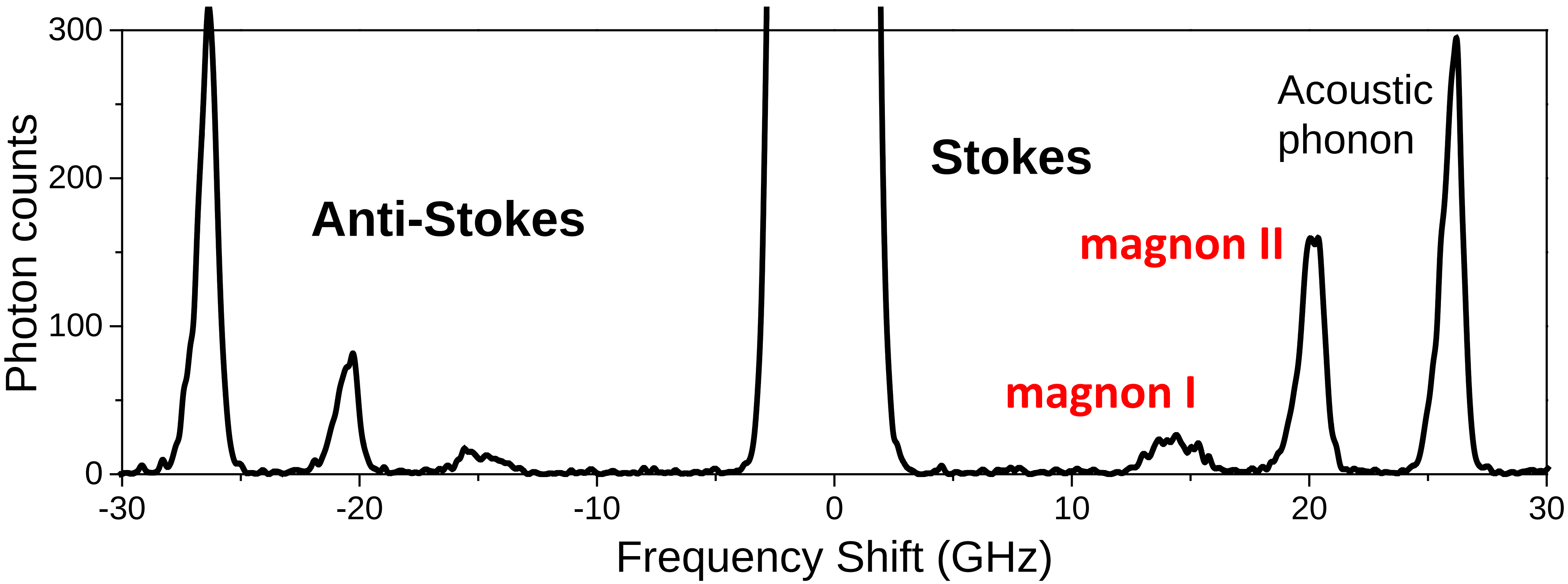


Pumping one disk while the other is 'dark' leading to PT symmetry



Brillouin scattering spectrometer for magnon spectroscopy





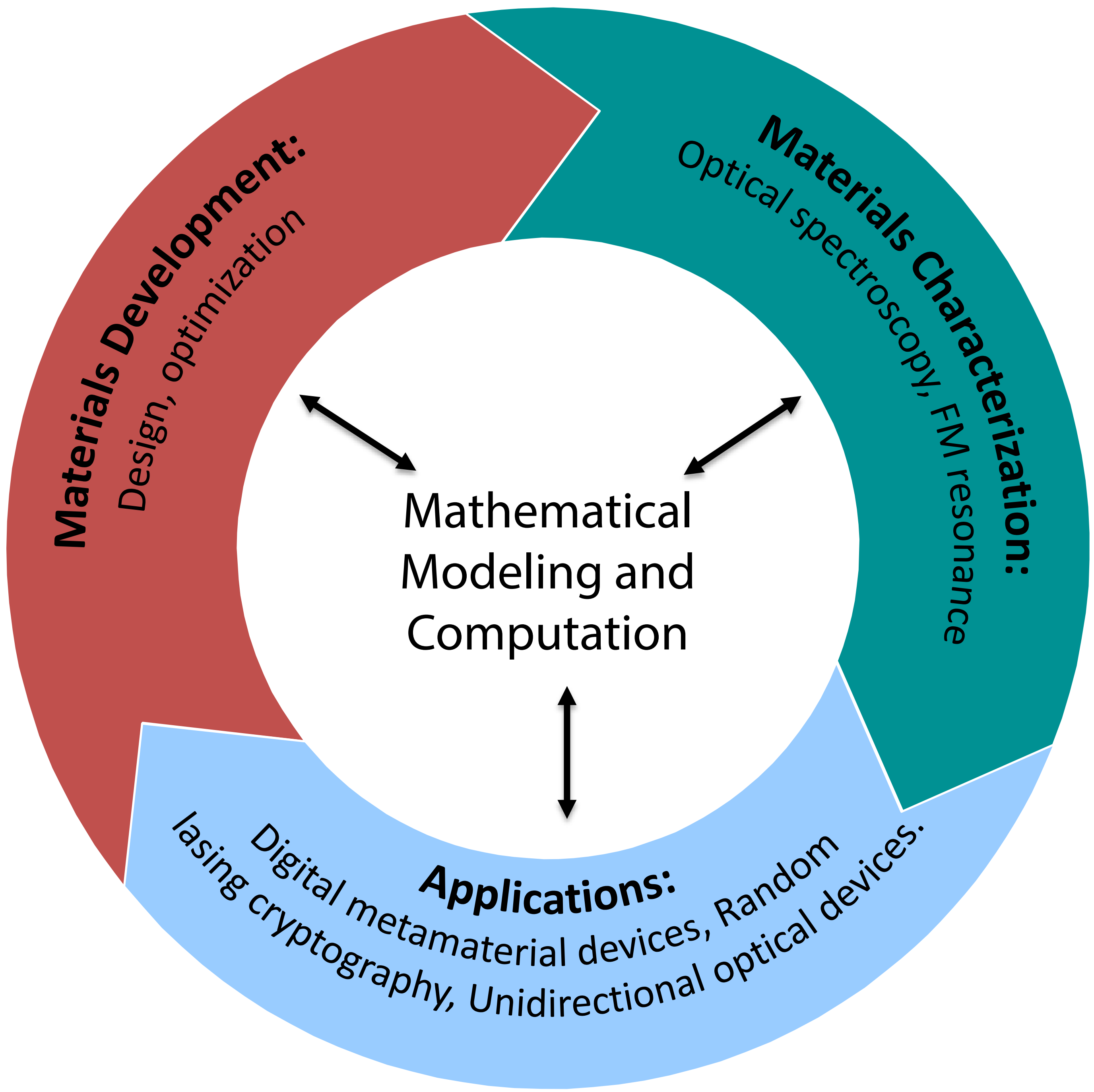
Impact of FRG3

- Optical devices based on PT symmetry; commercialization
- Realization of PT symmetry in nonlinear optics
- Achieving magnonic gain in FM
- Magnetic devices based on magnetic PT symmetry; commercialization

Research Effort for IRG

Trainees
3 Postdocs
5 PhD students
4 REU students

Collaborations
Univ. Wisconsin
NREL
Oakridge Natl. Lab
Georgia Tech
Wesleyan, LANL



Industrial Partnerships
Intel, Simpetus, LLC
LumArray Corp., Samsung

International Collaborations
Technion, Sogang U (Korea),

What defines success of the IRG?

- Significant advances in the mathematics of material design.
- Create a library of DMM-based integrated devices for commercial applications.
- Finding unique properties of RL in chiral materials.
- Commercialization of RL imaging in medical applications.
- Optical devices based on PT symmetry; commercialization.
- Achieving magnonic gain in FM.