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| **2024 Boston University ECE Summer Research Projects** | | | |  |
| Project title | Project Description | Mentor | openings | applicants |
| Multiple-element Photoacoustic Array for Retina Stimulation | Modulating neural activities is essential for understanding brain and for new clinical treatments. In this project we are focus on demonstrating a photoacoustic interface (for example, *ACS Nano*, 16, 2, 2292–2305) to achieve high spatial resolution (sub 100 microns) with multiple element parallel capability, both of which are essential for retinal and vision cortex stimulation helping blindness. In this study, students will participate in design the programmable optics, fabrication of biocompatible focus photoacoustic arrays, and measurement of electrical response of retina. | Chen Yang  <https://sites.bu.edu/yanglab/> | 2 |  |
| Photoacoustic fiber emitter for volumetric brain stimulation | Brain stimulation is important for non-drug treatment for neurological disorders and for brain machine interface. In this project we will further develop a photoacoustic fiber device (Adv. Health Mat.,2300430; *Nat. Comm*, 11, 881) provide a multi-site stimulation with controlled stimulation location and volume through tuning the light path in the fiber to aim at specific area of optoacoustic coating on a fiber can control the location and size of generated US, therefore achieving volumetric optoacoustic stimulation. Students will develop a fiber device with active stimulation volume controllability and characterize the tunable US field generated. |  |
| Chemical imaging with artificial intelligence. | In this project, we will use machine learning and large language model (ChatGPT) to pick small signal from noise and to optimize the chemical microscope design. Student will have change to learn computational neural network or the large language model and apply these tools to advance computational chemical imaging (for a recent example, Science Advances, 2023, 9, eadg8061). | Ji-xin Cheng  <https://sites.bu.edu/cheng-group/> | 1-3 |  |
| Stimulated Raman photothermal microscopy towards ultrasensitive bond-selective imaging | Stimulated Raman photothermal microscopy is a very recent invention in our group (Science Advances, 2023, 9, eadi2181). In this summer project, we will advance this project via developing a Stimulated Raman photothermal microscope using a compact fiber OPO towards commercialization and clinical transition. |  |
| App-based detection of antibiotic resistance | Antibiotic resistance is a great challenge in the post-antibiotics era. In this project, we will use an azide photothermal probe (App), together with a mid-infrared photothermal microscope, to probe bacterial or fungal response to antibiotics at single cell level. This project is based our recent development of video-rate MIP microscopy (Science Advances, 2023, 9, eadg8814) and photothermal reporters (Nature Methods, Jan 2024) |  |
| Physics & Applications of Singular Light | When we think of light, we think of a Gaussian-shaped spot, usually traveling in a straight line except when it encounters interfaces. This is, however, only the first, fundamental solution of the wave equation – much as a guitar string can have many modes (and frequencies) of vibrations, so can light also exist in different eigenstates. These peculiarly shaped light beams are characterized by singularities – i.e., regions in which some quantity does not have a well-defined value – in polarization, phase or amplitude. The physics of propagation of such beams reveals exotic effects, such as the ability of the beam to self-heal past obstructions (Bessel beams), the ability to carry orbital angular momentum (OAM) that makes light travel in helical paths rather than a straight line, or even the possibility of retaining memory of the paths that it takes. Analogous to the physics of tornadoes as well as electron orbitals, these beams reveal several unique classical and quantum properties not normally observed with conventional Gaussian beams. We study these fundamental properties and also apply them to varied applications such as high-capacity classical communications that consume low energy per bit, high-speed metrology including object sensing for autonomous systems as well as spectrometry and imaging. | Siddharth Ramachandran  <https://sites.bu.edu/ramachandranlab/> | 1-2 |  |
| Spatio-temporal & Ultra-fast Microscopy | Optical imaging techniques such as fluorescence, confocal, or multiphoton microscopy, have allowed scientists to study the properties and function of living biological tissues, such as the mammalian brain. However, refractive index inhomogeneity in living tissue leads to scattering of input light fields, which reduces the penetration depth at which useful information about the sample can be gleaned. We aim to study how tailoring of nonlinear interactions between ultra-fast pulses of light – both inside and outside of biological samples – can be used to enhance signals from deep within the tissue. Furthermore, we study how the use of structured light – i.e. light with spatial profiles more complex than a conventional Gaussian beam – can be used to improve information throughput in biological imaging in order to develop state-of-the-art microscopy methods for neuroscience and life science at large. |  |
| Nonlinear & Quantum Photonics | Nonlinear optical phenomena represent the interaction of light with the material in which it propagates, resulting in myriad effects such as the ability to controllably alter its color and shape in both time and space. Because such effects perturb the principle of superposition in linear optics, nonlinear optics is one of the best known means of generating quantum entanglement. We study new nonlinear optical phenomena enabled by singular and structured light beams, such as new modal selection rules for Raman & Brillouin scattering and the ability to obtain hyper- or hybrid-quantum entanglement. We then exploit these unique effects for applications such as single-photon frequency conversion for quantum networks, and for developing high-power lasers in the long-pulse as well as ultra-fast regime, for myriad uses ranging from biomedical imaging to LIDAR-based sensing and underwater communications. |  |
| Deep Optics for Computational Microscopy. | We are developing physics embedded deep learning algorithms to enable novel designs of optical components for computational microscopy.  Interested students are expected to have a solid understanding of Fourier Optics and be comfortable with computational tasks in Python. | Lei Tian  <https://sites.bu.edu/tianlab/> | 1 |  |
| Acousto-optic imaging with an event camera | Event cameras are a new camera technology where photon detection events are recorded asynchronously without the use of a frame clock. These cameras are designed to image changes in scenes, rather than the scene itself. As such, these cameras may be useful for acousto-optic imaging, where changes are induced by the insonification of a sample with an ultrasound pulse. The student working on this project will build a prototype system to test this hypothesis. This will involve learning about event cameras, ultrasound pulser/receivers, and speckle. | Jerome Mertz  <https://sites.bu.edu/biomicroscopy/> | 1 |  |
| Parallax-gated direct-time-of-flight lidar | The objective of this project is to demonstrate a direct-time-of-flight lidar that leverages novel `parallax gating’. The proposed system uses a SPAD array with neighboring pixels grouped into unit cells. A unit cell outputs a single measured histogram composing the counts from all of the SPADs within it. Each unit cell has a companion laser spot, and the system geometry is designed such that the spot falls within its companion unit cell over a useful range of distances.  By introducing a baseline distance between the projector and the sensor, the change in position of the laser spot within the unit cell due to change in the target's distance (parallax) can be calculated. The spot can only fall on a specific SPAD in a unit cell given that the target distance falls within some range, and hence the laser pulse arrives within some window smaller than the full integration time. This window can be calculated a priori or calibrated/measured for every SPAD.  Then, by applying a time gate to each SPAD to reject ambient photons arriving outside the window of possible pulse arrival times, the signal-to-background ratio of the measured histogram can be improved, ultimately resulting in improved accuracy and precision of the depth measurement. | Vivek Goyal  <https://vivekgoyal.org/> | 1 |  |
| Exploring the Multi-agent Approach for Automating Microscopy Experiments | Artificial intelligence (AI) has demonstrated substantial potential in accelerating scientific research through automated experimental design and execution [1,2]. The use of AI agents built upon large language models offers distinct benefits: firstly, they can be readily tailored to specific tasks through the integration of domain-specific knowledge extracted from literature; secondly, they can interface directly with the physical world via the programming interfaces experimental equipments. In this project, we will explore the approach of building a mixture-of-experts (MoEs) system [3] — each AI agent is trained to be an expert in a specific task but meanwhile is required to coordinate with other agents to contribute to a single goal — to automatically design and conduct optical imaging experiments. We will investigate and evaluate the abilities of several commercially available and open-source models to automate typical adaptive imaging experiments conducted on a diverse array of experimental platforms, ranging from widefield to multiphoton microscopy.  [1] Wang, Hanchen, et al. "Scientific discovery in the age of artificial intelligence." *Nature* **620**, 47-60 (2023).  [2] Boiko, Daniil A., et al. "Autonomous chemical research with large language models." *Nature* **624**, 570-578 (2023).  [3] Jiang, Albert Q., et al. "Mixtral of Experts." *arXiv preprint: 2401.04088* (2024). | Tianyu Wang  <https://tyw-lab.github.io/> | 1 |  |
| Elucidating Multiphoton Excitation with Quantum State of Light | Multiphoton microscopy (MPM) is the workhorse for deep-tissue imaging for its ability to acquire 3D fluorescent images through highly scattering biological tissues -- a property indispensable for minimizing invasiveness for in vivo imaging. The ability of MPM to image through biological tissue relies on multi-photon excitation (MPE) of fluorescence, a nonlinear process that favors high light intensity for fluroescence generation. However, as a trade-off, the nonlinear excitation is often accompanied by weak fluorescent signals, which in turn limits imaging speed and depth. More recently, there has been a resurgence of interests in investigating the possibility of using quantum light (i.e., the state of light could not be described or generated purely through classical models of light) to enhance MPE. However, many mysteries persist. Most notably, it is still an open question if any quantum state of light would yield any practical advantage over classical light for deep-tissue imaging, in terms of signal and background strength. To address this question, we aim to develope a clear theoretical framework to treat the interaction of fluroescent molecules and more generic forms of quantum light, not limtied to biphoton pairs generated by spontaneous parametric down conversion [1]. This project will focus on summarizing literature, conducting numerical experiments, and eventually achieve the goal of developing a physical model that is compatible with MPE with arbitrary quantum light.  [1] Dayan, Barak. "Theory of two-photon interactions with broadband down-converted light and entangled photons." *Physical Review A* **76**, 043813 (2007). | 1 |  |
| Quantification of the Computational Capacity of Multi-plane Scattering of Light | Multi-plane light scattering is a technique capable of effectively emulating arbitrary unitary transformations on light fields, with burgeoning applications in optical computing [1], communication [2], and imaging [3]. Recent research [4,5] has demonstrated that this multiple scattering through this method can extract image features through non-linear operations, despite utilizing inherently linear optical components. Yet, the degree to which multi-plane light scattering parallels the capabilities of deep neural networks remain an unresolved question. This study is dedicated to simulating multi-plane light scattering in 3D space, through planes of arbitrary scattering patterns. Leveraging this simulation tool, we will conduct a series of numerical experiments to quantify the computational capacity of multi-plane scattering's non-linear processing abilities in the context of image analysis.  [1] Lin, Xing, et al. "All-optical machine learning using diffractive deep neural networks." \*Science\* \*\*361\*\*, 1004-1008 (2018).  [2] Fontaine, Nicolas K., et al. "Laguerre-Gaussian mode sorter." *Nature communications* **10**, 1865 (2019).  [3] Cheng, Xiaojun, et al. "Development of a beam propagation method to simulate the point spread function degradation in scattering media." *Optics letters* **44**, 4989-4992 (2019).  [4] Xia, Fei, et al. "Deep Learning with Passive Optical Nonlinear Mapping." *arXiv preprint: 2307.08558* (2023).  [5] Yildirim, Mustafa, et al. "Nonlinear Processing with Linear Optics." *arXiv preprint: 2307.08533* (2023). | 1 |  |
| First-principles modeling of the electronic properties of nanomaterials | To design new materials for nano electronics, we need to understand the relationship between atomic-scale and macroscopic properties. The undergraduate students will run simulations and analyze the fundamental physical properties of low-dimensional materials. A background in python, modern physics, quantum mechanics or solid-state physics is helpful. | Sahar Sharifzadeh  <https://sites.bu.edu/sharifzadeh/sahar-sharifzadeh/> | 1 |  |