IITB-Monash Research Academy

Indian Institute of Technology Bombay | MONASH University

An Indian-Australian research partnership

Project Title:	**Ultrafast manipulation of light at the nanoscale with hybrid nanostructures**
Project Number	**IMURA0287**

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Research Academy Themes:

Highlight which of the Academy's Theme(s) this project will address?

(*Feel free to nominate more than one. For more information, see www.iitbmonash.org)*

1. Advanced computational engineering, simulation and manufacture
2. Infrastructure Engineering
3. Clean Energy
4. Water
5. Nanotechnology
6. Biotechnology and Stem Cell Research

The research problem

Define the problem

The ultimate goal of optics is to understand the light–matter interaction at the microscopic level and to enable a perfect control over it. This goal has been brought closer by the recent advances in spectroscopy, enabling investigations at extremely short spatio-temporal scales; and in nanotechnology, making the fabrication of complex optical structures possible. Artificially engineered composites made of different types of nanostructures (e.g., metal, semiconductor, and dielectric components that are much smaller than the wavelength of light) open up unlimited possibilities to control electromagnetic interactions, including high optical nonlinearity, negative refraction, optical cloaking, and ultrafast response. The concept of composite nanostructured materials has drastically altered our way of thinking about light–matter interactions and greatly enriched the field of optics. It has become apparent over the last decade that light propagation can be manipulated at will using artificially fabricated structures with prescribed optical properties, the diversity of which is limited only by the imagination of the researchers and sophistication of the fabrication techniques. This new understanding has revolutionized the design paradigm of photonic devices and quickly resulted in the experimental demonstration of several counterintuitive effects with far-reaching breakthrough applications. Today, scientists and engineers all over the world are combating the fundamental and technological challenges that deter practical use of the exciting functionalities offered by hybrid nanostructures. The challenges in the field that remain outstanding include: (i) microscopic understanding of the light–matter interaction in hybrid nanostructures; (ii) compensation for absorption losses; (iii) enabling electrical and all-optical functionalities and (iv) nanofabrication of large-scale hybrid nanostructures/metamaterials with sub-50-nm resolution. This project will mainly address the first three of these challenges.

Project aims

Define the aims of the project

This PhD project aims at designing, fabricating, and studying prototypical hybrid nanostructures with superior performance and enhanced nonlinear response to both electrical and magnetic fields of the incident light. With the engineering of such nanostructures, the PhD student will explore and describe the fundamental physics governing their optical response, as well as bring the functionalities of hybrid nanostructures closer to practical needs. He/She will also perform *fundamental research aiming at suggesting, optimizing, and demonstrating theoretically and/or experimentally novel approaches for controlling light at the nanometric lengthscale and ultrafast timescale*.

This project pursues several main goals, all of which are expected to uncover new physical phenomena and deliver high-impact research outcomes:

- Theoretical demonstration of the active optical functions by conducting detailed numerical simulations of light propagation through tunable hybrid nanostructures/metamaterials and optimization of their design.
- Fabrication of prototypical hybrid nanostructures using focused ion beam, e-beam or optical lithography and various material deposition techniques.
- Experimental investigation of the optical response of the hybrid nanostructures/metamaterials using ultrafast as well as other spectroscopic techniques aimed at understanding the optical response at microscopic level.
- Theoretical and experimental demonstration of gain in hybrid nanostructures/metamaterials by comprehensively studying two fundamental approaches to overcome the intrinsic absorption in metals: (i) introduction of active amplifying materials, e.g., semiconductor quantum well or quantum dots or organic molecules into the design of meta-atoms; and (ii) embedding nonlinear materials into the metal–dielectric composites to realize optical gain.
- Identification of novel concepts for hybrid nanostructure/metamaterial-assisted guiding and control over the optical beam and its deep subwavelength confinement by considering different designs of meta-atoms, operation schemes, guide geometries, and arrangements of meta-atoms, or by following other nontrivial paths for harnessing the advantages offered by tunable metamaterials and/or hybrid nanostructures.

Expected outcomes

Highlight the expected outcomes of the project

The proposed project is of strategic interest to both India and Australia because of its prospective industrial, economic, and social impacts. It will introduce and demonstrate *novel concepts for the realization of tunable integrated optical devices based on hybrid nanostructures and/or metamaterials (e.g., frequency converters, optical switches, nano-lasers, amplifiers, beam spatial transformers, etc.)*, which may result in immediate applications in photonics, imaging, sensing, and even solar-cell technologies. Furthermore, through the creation of extensive theoretical and experimental knowledge and by suggesting practical applications at the leading edge of photonics—highly multidisciplinary field of optically active nanostructures—the project will make significant contribution to the designated priority areas. It will help to build and maintain global competitiveness of both the countries in the rapidly developing field of nano-photonics, which is currently a hot research topic being actively pursued at leading research centres around the world.

This project will also give India and Australia a world-leading technology with potential future commercialization, and strengthen their stake in the optoelectronics industry. It is important, therefore, that the intellectual property (research publications and patents)—which will emerge as a result of the project—be protected through the well-established mechanisms at IITB-Monash Research Academy. The joint work of the Advanced Computing and Simulation Laboratory (headed by Prof. Malin Premaratne) and the research group from the Physics Department (headed by Assist. Prof. Parinda Vasa) initiated by the proposed project will result in excellent international publications as well as significant technology and knowledge transfer between IITB and Monash University in turn leading to gaining valuable experience by the two research groups.

The realization of the project by a student from the Physics Department will give him/her unique skills and knowledge in the rapidly developing area of nano-photonics and eventually increase the competitive strength of India/Australia in cutting edge research as well as high-tech market. These, and potentially other, outcomes of this PhD research project are vitally beneficial to both India and Australia via either publicizing India's and Australia's excellence through high-quality research, creating strong international relations; development of human capital, enhancing collaboration and research efficiency, and supporting local industry.

How will the project address the Goals of the above Themes?

Describe how the project will address the goals of one or more of the 6 Themes listed above.

The PhD project is developed to perform the research in novel directions in the most efficient way, and to thoroughly address the goals of the research themes "*Nanotechnology*" and "*Advanced computational engineering, simulation and manufacture*". The PhD student will use the contemporary methods of optics and mathematical physics, as well as the commercially available software (such as FullWAVE or COMSOL), to extract the magnetic permeability and electric permittivity of a given three-dimensional nanostructures. The student will learn to use the state-of-the-art fabrication and ultrafast spectroscopy facilities at IITB, in order to experimentally investigate the hybrid nanostructures. He/she will then perform analytical and semi-analytical theoretical as well as experimental studies of the optical response with the emphasis on identifying novel effects and the optimal schemes for the light manipulation strategies essential for the project. During the entire span of the project, the student will effectively combine the theoretical (Monash) and experimental (IITB) techniques to achieve the ambitious goals of the proposed project.

Capabilities and Degrees Required

List the ideal set of capabilities that a student should have for this project. Feel free to be as specific or as general as you like. These capabilities will be input into the online application form and students who opt for this project will be required to show that they can demonstrate these capabilities.

The student must have a strong theoretical and/or experimental background in optics (including extensive courses of electrodynamics, solid-state physics, and nanotechnology).

A GPA score above 3.9 (out of 4), and Academic-IELTS scores of 7 (out of 9) or above for each test component (listening, reading, writing, and speaking) is required. For Indian students, CPI above 7 (out of 10) or above 75% in B.E./B. Tech/MSc/M.E/M.Tech in Physics/Engineering Physics/Electrical engineering/Photonics and GATE/NET score of above 90% is necessary.

It is also desirable to have at least one journal and/or several major conference publications. The student will have to appear before a selection committee interview.