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1. Cover Page

Title: Nanophotonics and Optical Nanomaterials

Basic Energy Sciences: Scientific User Facilities Division, NSRC

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Funding Request (by year)

	FY16 ($K)	FY17 ($K)	FY18 ($K)	Total ($K)
Total	3,516	3,669	3,805	10,990

Human Subjects Use: No
Animal Subjects Use: No

Signatures:

Stephen Doorn, PI, LANL Date

Tanja Pietrass, Division Leader Date

Grant Heffelfinger, Director Date

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2.0 Table of Contents

3.0 Tabular Budget and Staffing Summary

Total Budget and Level of Effort

Nanophotonics and Optical Nanomaterials

Total Operating Budget by Subtask

Requested Funding	FY16 ($K)	FY17 ($K)	FY18 ($K)	Total ($K)
Total	3,516	3,669	3,805	10,990

(Annual budgets cover loaded salaries, small purchases, postdoc salaries, and travel.)

Level of Effort

Key Personnel	FY 13 (FTE)	FY14 (FTE)	FY15 (FTE)
Brener*	0.6	0.6	0.6
Camacho	0.5	0.5	0.5
Chen	0.5	0.5	0.5
Doorn*	0.75	0.75	0.75
Efimov	0.5	0.5	0.5
Htoon	0.5	0.5	0.5
Hollingsworth	0.5	0.5	0.5
Ivanov	0.5	0.5	0.5
Luk	0.5	0.5	0.5
Prasankumar	0.5	0.5	0.5
Technicians	0.5	0.5	0.5
Postdocs	2	2	2

*Thrust Leader and Partner Science Leader

Materials and Supplies

Requested Funding	FY16 ($K)	FY17 ($K)	FY18 ($K)	Total ($K)
Total	336	385	413	1,134

4.0 Management Plan

4.1 Overarching Center Goals

The opportunities presented by nanomaterials are exciting and broad, with revolutionary implications spanning energy technologies, electronics, computing, sensing capabilities and biomedical diagnostics. Deriving the ultimate benefit from these materials will require the controlled assembly of diverse nanoscale materials across multiple length scales to design and achieve new properties and functionality, in other words, nanomaterials integration.

Integration has played a pivotal and revolutionary role in the development of nearly all science and technology. Perhaps the most familiar and dramatic illustration is the development of very large-scale integrated circuits where active and passive devices based on semiconductors, dielectrics, insulators, and metals are monolithically integrated on a single platform for specific applications. Even greater challenges exist as nanomaterials are integrated into new architectures to form functional systems. Interfaces and defects are formed whose structures and properties can dominate the chemical, mechanical, electronic and optical properties of the system. The effects of synthesis and fabrication processes on performance must be investigated and new directed- and self-assembly approaches developed for greater functional control. Combined bottom-up and top-down synthesis and assembly techniques must be optimized and/or invented to allow the intention design of hierarchical materials. Establishing the fundamental principles that underpin the integration of nanomaterials that display unique properties, such as quantum confinement, is of paramount importance to nanoscience and ultimately nanotechnology.

The goal of the Center for Integrated Nanotechnologies (CINT) is to plays a leadership role in integration of nanostructured materials to enable novel capabilities and applications through its function as a Department of Energy/Office of Science Nanoscale Science Research Center (NSRC) national user facility. By coupling open access to unique and world-class capabilities and scientific expertise to an active user community, CINT supports high-impact research that no other single institution could achieve – the whole of CINT including its user community is greater than the sum of its parts.

4.2 Overarching Thrust Goals

The Nanophotonics and Optical Nanomaterials (NPON) Thrust in CINT seeks to address the overall scientific challenge of understanding and controlling fundamental photonic and electromagnetic interactions in nanostructured optical materials fabricated using both chemical and physical synthesis. The NPON thrust's scientific focus areas reflect efforts towards the design, synthesis, fabrication and assembly of optical nanomaterials, the characterization of these structures, and the integration of these materials into optical devices and systems. Integration is of paramount importance in our thrust and a few examples are: the integration of new optical nanoparticles into more complex optical devices such as light emitters or detectors; the use of basic metamaterial structures integrated with doped layers and contacts in order to build optical modulators; the integration of plasmonic nanocavities or nanostructures with optical emitters in order to alter their radiative rates and optical emission properties. Major research areas in the thrust are: 1) Chemical and Physical Synthesis of Optical Low-Dimensional Nanophotonic Structures; 2) Optical Properties of Low-Dimensional Nanostructures; 3) Metamaterials and Nanoplasmonics. These areas have evolved from our collaborations with our extensive user base.

Synthesis, Processing, and Manipulation of Low-Dimensional Nanostructures

Research in this area includes colloidal synthesis, processing, and reaction chemistry of semiconductor, noble-metal and magnetic-metal nanostructures having controlled shape (anisotropy), surface chemistry (reactivity), and crystal structure (semiconductor properties), as well as hybrid, multifunctional (e.g., magneto-optical, electro-optical, and multiferroic) nanomaterials comprising different combinations of semiconductors (e.g. quantum dots, nanowires, carbon nanotubes) and metals, inorganics and organics, colloidal and epitaxial structures, and complex transition metal oxides. A growing focus in NPON materials development is on design and control of interfacial interactions in multi-component systems as a powerful route towards creating coupled, additive, or emergent behaviors.

This thrust area also includes lithographic methods which are applied to the fabrication of two- and three-dimensional nanophotonic structures such as nanowire arrays and metamaterials. We actively utilize the Integration Laboratory at the CINT Core Facility, which includes a 9000 ft^2 Class 1000 clean room and allows the capability for state-of-the-art nanofabrication. Finally, in addition to conventional colloidal synthesis of functional nanomaterials, we have developed advanced capabilities for automated and flow-enabled synthesis of semiconducting quantum dots and nanowires. Together, these new capabilities permit rapid exploration of the synthetic phase space for advancing the discovery and optimization of complex hetero-structured optical nanomaterials and enable unprecedented control over interfaces in nanowire heterostructures. Multi-materials integration efforts are being advanced by our ability for precise placement of solution-prepared nanostructures into fabricated structures (e.g., use of dip-pen nanolithography for "writing" semiconducting nanoemitters onto the active areas of photonic crystal assemblies, cavities, and plasmonic and metamaterial structures).

Optical Spectroscopy and Characterization of Low-Dimensional Nanostructures
Here, we use our unique capabilities in advanced ultrafast and single-nanostructure spectroscopies to explore energy transformation at the nanoscale, from energy and charge transfer to electronic relaxation and quantum-to-classical emission behaviors across multiple length-, time-, and energy scales. Such phenomena will contribute to light harvesting applications (photovoltaics, photodetection, and radiation detection), as well as to light emitting applications (solid-state lighting, LEDs, lasing, etc.). In particular, we will investigate time-and-spatially-resolved processes in individual quantum emitters and for those coupled to some external nanocavity or medium, extending our previous studies of these systems. Also noteworthy is our ability to utilize ultrafast optical microscopy for probing temporally and spatially resolved dynamics in NWs and other nanoscale systems. Furthermore, we will use ultrafast optical and terahertz (THz) spectroscopy to understand and control competing interactions between superconducting, ferromagnetic, and ferroelectric phases in nanostructured metal-oxide films, in a broad collaboration with the NEM and TSNP thrusts. From quantum emitter hetero-assemblies to studies of layered multiferroic oxides, an emerging focus in NPON is thus aimed at creating and understanding emergent phenomena arising from multiple materials interactions.

Metamaterials and Nanoplasmonics
As a key component of NPON interests in creating hybrid materials interactions for generation and manipulation of light, the preparation and fabrication of novel metamaterials and nanoplasmonic structures allow us to study and control collective and emergent electromagnetic phenomena. In this area, we specifically explore the phenomena that form the foundation and future of nanophotonics: plasmonics, and metamaterials defined in the broadest sense (effective media, resonator based, and photonic crystals). This area thus spans research ranging from functional photonic materials, to novel phenomena, to device integration. Some specific directions that we propose are to explore novel nanostructures for manipulating light propagation in new ways, active metamaterials at infrared to visible frequencies, and the integration of gain/functional media with plasmonic and metamaterial structures in order to realize optoelectronic devices with enhanced performance and study fundamental issues of light matter interaction.

4.3 Staffing Resources
The NPON thrust draws on a combination of scientific strengths and facilities that allows it to conduct research and provide user interactions not easily achievable elsewhere. Both Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL) have long histories of excellence in the areas of nanophotonics and the physical and chemical synthesis of nanomaterials, while SNL is a world leader in nano- and micro-fabrication and LANL personnel remain at the forefront in advanced optical spectroscopies and optical interaction physics.

Each CINT thrust is managed through one thrust leader and a corresponding partner science leader, one from each of the two labs. This management structure is beneficial for ensuring close coordination and teaming across the thrust as well as enhancing CINT's in-reach into both Los Alamos and Sandia infrastructure. The NPON leaders are Stephen Doorn (Thrust Leader, LANL) and Igal Brener (Partner Science Leader, SNL): both are internationally renowned experts in the field of nanophotonics and spectroscopic characterization of nanomaterials and provide technical leadership to NPON scientists from both LANL and SNL.

NPON thrust members span the scientific areas noted above, which allows the development of multidisciplinary teams to address the wide range of research activities included in the NPON thrust. Brief descriptions of key personnel and their research interests are included below (in alphabetical order) to illustrate how each member contributes to the scientific work of the thrust. (See the biographical sketches for more in-depth descriptions of staff and activities).

Stephen Doorn (Thrust Leader; LANL, Gateway) – Stephen is a physical chemist whose interests are in spectroscopic characterization of carbon nanomaterials, including graphene, graphene oxide, and carbon nanotubes. Current efforts include spectroscopic investigation of fundamental electronic structure and optical properties, optical control via covalent and noncovalent functionalization chemistry, redox behavior, chirality-selective reaction chemistry, and nanotube separations.

Igal Brener (Partner Science Leader; SNL, Core) – Igal is a physicist with experience in semiconductors, ultrafast science, optical chem/bio sensors, silicon photonics and metamaterials. His current research involves linear and nonlinear THz and IR metamaterials, nanoplasmonic phenomena and the interactions between semiconductor nanostructures and dielectric/plasmonics cavities and metasurfaces.

Ryan Camacho (SNL, Core) – Ryan is a physicist with research interests in nano-optomechanics and quantum nano-photonics. His activities involve the development of integrated quantum photonic nanomaterials and devices for communications, information processing, and nonlinear optics.

Hou-Tong Chen (LANL, Gateway) – Hou-Tong is a physicist whose research interests mainly focus on metamaterials and metasurfaces in the terahertz and infrared frequency ranges. His current research activities include the creation of novel metamaterial structures with emerging properties and integration of functional materials with metamaterial structures in order to realize active/dynamic functionalities.

Anatoly Efimov (LANL, Gateway) – Anatoly's expertise is in the area of ultrafast nonlinear optics. His research interests include photonic crystal fibers and devices; femtosecond pulse shaping and coherent control with adaptive feedback; nanoplasmonics, focusing on the underlying fundamental science and applications of propagating plasmon-polaritons; active nanophotonic devices; and graphene.

Jennifer Hollingsworth (LANL, Gateway) – Jennifer is a synthetic chemist whose focus is on the development of novel heterostructured optical nanomaterials and hybrid structures, and establishing structure-function relationships toward intentional design of new functional nanomaterials. She also advances the state-of-the-art in synthetic methods, using flow-based, automated, and/or in situ characterization methods for quasi-combinatorial/rapid-throughput synthesis of nanowires and "giant" quantum dots.

Han Htoon (LANL, Gateway) – Han is a condensed matter physicist whose focus is on investigation of fundamental photophysics and quantum optics of semiconductor nanostructures (nanocrystals, nanowires, carbon nanotubes, etc.) and metal-semiconductor hybrids using low temperature, high spatial, spectral and temporal resolution optical imaging and spectroscopy techniques. He is also actively involved in the development of novel single nanostructure spectroscopy techniques and prototype classical/quantum light sources.

Sergei Ivanov (LANL, Core) – Sergei is a synthetic chemist whose current research interests focus on colloidal synthesis of core-shell heterocomposites for optical and photovoltaic applications, the synthesis and properties of chemically doped colloidal nanostructures, and the design and synthesis of alloy and hybrid colloidal metal/ semiconductor nanostructures with new functionalities.

Willie Luk (SNL, Core) – Willie is a physicist whose research focuses on using photonic crystals and metamaterial nanophotonic structures to control photonic density of states. Current activities center on epsilon-near-zero materials for spectral control of absorption/emissions for renewable energy applications.

Rohit Prasankumar (LANL, Core) – Rohit is a physicist with research interests centering on the measurement of nanoscale material properties over a broad frequency range (ultraviolet to terahertz) using ultrafast optical spectroscopy, as well as the development of novel diagnostic techniques for temporally and spatially resolving dynamical phenomena in nanoscale materials. Materials studied are primarily semiconductor nanostructures, Dirac materials, and correlated electron systems.

The staffing in NPON currently comprises 10 CINT Scientists and 2 technologists, who are further supported by 15-20 postdoctoral researchers. Research in the NPON thrust builds upon strong collaborations among the thrust members, other thrusts, and CINT users.

A particular strength of NPON is the strong collaborative effort between Thrust members who focus on the discovery and synthetic development of new optical nanomaterials (quantum emitters) and those who focus on elucidating and harnessing new fundamental photophysical properties. This synergy and cooperative feedback process is exemplified by the Hollingsworth-Htoon and Doorn-Htoon collaborations, which have resulted in new quantum dot and carbon nanotube materials, respectively, while at the same time enabling groundbreaking studies of nano/mesoscale optoelectronic materials properties. Collaborative efforts within NPON thus encompass 0-D to 1-D materials and their higher-order assemblies and, through chemical and physical modifications, the ability to controllably induce localization effects in 1-D systems to yield emergent emission behaviors for further study. The 1-D realm also encompasses nanowires (NWs), with the Hollingsworth-Prasankumar collaboration (with additional ties to Yoo in the NEM thrust) resulting in ultrafast studies of carrier relaxation and diffusion processes enabled by solution-based synthesis of NW heterostructures. These synergistic efforts also are creating a natural link to integration of low-D emitters with plasmonic and all-dielectric metamaterials under development within NPON.

In the area of collective and emergent electromagnetic phenomena, the members of the NPON thrust investigate multicomponent nanostructures as building blocks for new types of passive (e.g., polarization conversion and wavefront engineering) and active (e.g., nonlinear and tunable) metamaterials at higher optical frequencies than in previous work. Chen and Brener lead this effort, providing expertise in metamaterials design, device physics and advanced optical characterization, while working with Hollingsworth, Htoon, and Doorn on the integration of quantum emitters into the metamaterial framework. Clean-room fabrication (with Jia and Reno-NEM thrust) allows processing of metamaterials on a number of different semiconductor and oxide substrates. Related to these activities are studies of energy transfer and coupling between excitations in semiconductor nanoparticles and metallic nanostructures. These activities are led by Htoon, Hollingsworth and Luk, in collaboration with other members in the thrust, both for synthesis and measurements. As a new direction, a collaboration between Brener and Prasankumar is aimed at studying the dynamics of all-dielectric metasurfaces with ultrafast pump-probe spectroscopy.

In the area of quantum nanophotonics, thrust members study the generation, processing, and detection of light using quantum photonic nanomaterials. Efforts towards developing QD and CNT-based quantum emitters (Doorn, Htoon, Brener) are being integrated with capability for quantum device fabrication and testing led by Camacho and Luk. Such low-D photon sources will be coupled to novel quantum-optical circuitry available through the Camacho collaboration.

We also note that although the range of expertise in the NPON Thrust is broad, coverage in many areas is not sufficiently deep to sustain all desired activities. Our plan for covering these manpower deficiencies involves collaborations with other CINT thrust areas and interactions with CINT users, both described in more detail in Section 4.5 (Resources and Connections Across CINT).

4.4 Facility Resources

The other key components of the NPON thrust are facilities and capabilities. Our thrust has extensive activities in tool and instrumentation development. Additionally, the NPON thrust takes full advantage of the forefront synthesis, characterization, fabrication, and computational capabilities available at CINT, which include a 96,000 ft^2 Core facility at SNL and a 36,500 ft^2 Gateway facility at LANL, as well as other major non-CINT facilities at LANL and SNL.

Of particular importance to the NPON thrust are its extensive forefront spectroscopic capabilities, particularly ultrafast optical techniques and single nanostructure imaging and spectroscopy. Laboratories at the Core and Gateway provide a world-class suite of ultrafast optical excitation, diagnostic and measurement capabilities, spanning wavelengths from the ultraviolet to the far-infrared, with pulse durations down to 10 fs and ultrafast pulse shaping capabilities which can be configured for optical pump-probe, optical/mid-IR pump-terahertz probe and synchronized multi-beam experiments. Also, we have a home-made mid-IR time-domain spectroscopy system that allows angle resolved transmission and reflection, amplitude and phase measurements of a variety of samples between 7 and 14 μm. Additionally, thin films of materials can be characterized with IR, visible and UV variable angle spectroscopic ellipsometry (IR-VASE and V-VASE). For experimentally visualizing complex nonlinear optical processes in photonic nanostructures, waveguides and fibers, we have developed a unique Cross-Correlation Frequency-Resolved Optical Gating (XFROG) system. This novel characterization tool offers unprecedented resolution, sensitivity, and bandwidth and enables one to acquire a time and frequency portrait of the optical field, measured at the output of the device under study. The response of single nanostructures such as carbon nanotubes and nanocrystal dots, rods, and wires can be investigated with a variety of single-element spectroscopic and imaging diagnostics including photoluminescence (PL), photoluminescence excitation (PLE), wavelength and time resolved PL lifetime studies, photon pair correlation spectroscopy (PPCS)). Especially noteworthy is a new 4-channel, superconducting nanowire single photon detector integrated to these systems and capable of ultrafast fluorescence and photon correlation measurements in the 1 to 1.6 um wavelength range. All single element spectroscopies may also be performed as temperature dependent measurements down to 4K in optical cryostats. NPON also offers an extensively tunable (near-IR to UV) Raman capability as a probe of electronic structure, phonon coupling, and general materials characterization. Additionally, we share an FTIR with the soft-bio thrust that is routinely used to characterize IR metamaterial samples. Two microscope FTIRs operate at the core and gateway facilities, expanding our capabilities to measure polarized infrared reflection and transmission for small samples.

The NPON thrust also encompasses significant synthesis, including laboratories with multiple chemical fume hoods, inert-atmosphere glove boxes, microfluidic reactors, and automated chemical synthesis reactors that enable the efficient discovery and preparation of optically active semiconductor nanocrystals of various shapes (spherical QDs, rods, wires, multi-pods, platelets, etc.) as well as nanoparticles comprising metal oxides, simple metals, and/or magnetic materials. Solution-phase materials processing/integration capabilities include spin-coaters, Langmuir-Blodgett troughs, multi-well dipcoaters, and dip-pen nanolithography. CVD growth capability also exists for graphene and carbon nanotube synthesis. Associated characterization capabilities include UV-Vis-NIR spectrophotometers and fluorimeters for monitoring absorption and emission characteristics of the prepared nanoparticles, respectively, with attendant temperature-controlled sample holder and integrating sphere (for absolute QY measurements), as well as a UV-Vis-NIR time-resolved fluorimeter for rapid assessment of optical nanomaterial fluorescence lifetimes. Further characterization is available with multinuclear NMR spectrometers, an x-ray diffraction system for nanoparticle structural studies (with the versatility to analyze liquids and solids, powders, and thin films), and a simultaneous TGA/DSC analyzer for understanding of compound/material behavior at elevated temperatures, including enthalpic effects.

In the NPON thrust, we also have the necessary expertise and facilities to impact the area of nanointegration in the context of photonics. The Integration Laboratory houses state-of-the-art micro- and nanofabrication equipment to facilitate our vision to harness the nano and microscale phenomena for photonics applications. The NPON thrust uses extensively equipment in the CINT Integration Lab, a 9000 ft^2, class 1000 clean room, including a state-of-the-art electron beam lithography system (JEOL JBX-6300FS). The Integration Laboratory is of particular importance for the development of growth templates to provide preferential nucleation or assembly points for nanoparticles on various substrate materials, an essential capability in the NPON thrust. Furthermore, we have the background to leverage the most current nanofabrication techniques to realize, among other things, metamaterial and nanoplasmonic structures that are difficult or impossible to create in the typical 'university-style' cleanroom. Complementary capability includes a dip-pen nanolithography system for direct-write patterning from solution/liquid-phase "inks".

4.5 Resources and connections across CINT

Research in the NPON thrust is enabled by collaborations with members of the other three CINT thrusts. As examples, scientists in the TSNP thrust, particularly Tretiak, Trugman, and Zhu, are actively collaborating with NPON thrust members to develop models to understand, predict, and design functional response and emergent behavior in the area of photonics of multifunctional hybrid nanostructures, and collective and emergent electromagnetic phenomena in these nanoscale materials and structures. Significant efforts exist in modelling (by Trugman and Zhu) of the ultrafast optical response of one-dimensional nanowire materials, strongly correlated nanomaterials, complex transition metal oxides, and novel metamaterials of interest to the NPON thrust members (Prasankumar, Hollingsworth, Brener, Chen, Luk). In particular, ultrafast studies of multifunctional complex oxides (Prasankumar) are directly enabled by PLD growth of these materials within the NEM thrust (Jia). Furthermore, collaborations with Tretiak are an essential part of understanding optical behaviors of dopant states and exciton control in carbon nanotubes and are enabling studies of "molecular" nanotube model systems. Another collaboration between NPON and TSNP thrusts involves the joint project of Modine (TSNP) and Ivanov (NPON) to model the detailed interaction between components of semiconductor alloys to elucidate the reaction pathway leading to the formation of GeSn and SiGeSn semiconductor nanoparticles. Collaborations with scientists in the Nanoscale Electronics and Mechanics (NEM) thrust include those with Yoo in nanowire synthesis and device materials physics, as well as others involved in applications of nanowires towards energy harvesting. Close collaboration also exists between the Soft, Biological and Composite Nanomaterials (SBCN) thrust in the area of using quantum dots as light emitters for imaging purposes of particular for SBCN 3-D tracking needs. Finally, strategies for using bio-inspired approaches to materials integration is driving emerging efforts towards incorporation of nanoemitters into soft, responsive, reconfigurable matrices for modulation of nanoemitter interactions in soft materials systems.

Cross-thrust interactions have been an important component of developing NPON's integration efforts, with particular impact in the areas of metamaterial assemblies and development of NWs as energy harvesting devices. Nanowires are of interest for energy applications in that their unique structure retains 0-D like confinement effects, while their 1-D nature brings large absorption cross sections, enhanced transport, and potential for synthetically accessed multifunctionality. The synthetic expertise of Hollingsworth and Ivanov led efforts to incorporate NWs into mesoporous oxide sensitized solar cells through collaborative in-reach to LANL's C-Division with Milan Sykora. Close collaborations with Jinkyoung Yoo of CINT's NEM thrust advanced efforts towards integration of quantum dots with ZnO NW waveguides. Also with Yoo and Swartzentruber (NEM) are efforts at NW integration and characterization in thermoelectric devices. These efforts have benefited from a significant theory component (Piryatinsky, LANL T-4) as well. Important collaborations with the NEM thrust also exist in the area of developing novel integrated metamaterials as guided by theory (Trugman), through the use of oxide and superconductor substrates (Chen & Jia) and semiconductor heterostructures (Brener and Reno). In these efforts, we have tried to utilize the new degrees of freedom provided by nanoplasmonic or metamaterial structures in order to obtain new passive and active, linear and nonlinear, and tunable optical nanostructures and devices. Integration is the key to this activity as we combine different synthesized, grown or deposited materials with fabricated structures from the micro to the nanoscale.

While the primary goal of the CINT User Program is to enhance the research impact of the external User Community, the User Community also represents a valuable resource that greatly enhances CINT’s ability to conduct forefront nanomaterials research. Users contribute essential expertise to the NPON thrust in all of the research areas described above. As a strategy to complement existing capabilities within CINT, we have and will solicit external collaborations to leverage our expertise in critical areas of synthesis, fabrication, characterization and theory. For example, theoretical support from users for our efforts in nanowires and metamaterials will enable our research in these areas to progress more rapidly by enhancing our understanding of these systems and helping optimize their design for a given application. Quantum optics efforts in NPON in the areas of artificial atoms using Si and Ge defect centers in diamond, quantum receivers using superaddivive quantum circuits, quantum nonlinear optics in Lithium Niobate and Aluminum Nitride microresonators, and novel optical circuits and materials strongly overlap with an increase in high-profile users at CINT who are fabricating and testing devices for linear optics quantum computing, superconducting single photon detection, and single-photon "transistors". As another example, user interest in accessing NPON capability for generating and characterizing doped nanotube samples is providing direct access to a number of interesting photonic cavity and waveguide systems towards strengthening our overall effort in this exciting new area of study. Similarly, common interests in structure/function studies of core-shell gQDs is enabling the correlated multi-probe imaging efforts described in section 6.2 and 6.3.

4.6 Laboratory Complementary Resources and Inreach

In addition to the strong capabilities located within each of the dedicated CINT locations, the NPON thrust enjoys the benefits of leveraging existing facilities within the parent Laboratories. SNL provides access to world-class semiconductor cleanroom and growth facilities through the MESA complex. The extensive growth and fabrication hardware within MESA offer opportunities to leverage facilities for research that requires specialized equipment to fabricate optoelectronic devices. Further, CINT's major effort in the development of Discovery Platforms™ , modular, micro-laboratories that are designed and batch fabricated expressly for the purpose of integrating nano and micro length scales and for studying properties of nanoscale materials and devices, is enabled by the fabrication capabilities of MESA. These platforms provide a user friendly environment for scientists to explore and optimize the synthesis and measurements of nanomaterials. Additionally, the CINT Gateway offers close proximity to the National High Magnetic Field Laboratory (NHMFL), a National User Facility, allowing CINT scientists and users to perform forefront experiments in multi-shot magnetic fields up to 100T and even single-shot experiments to 300T using a suite of sophisticated diagnostics. Capabilities at the NHMFL are of particular interest for research developing multifunctional behavior in nanostructures when magnetic functionality is important. Finally, the Laboratory for Ultrafast Materials and Optical Science (LUMOS) at LANL contains one of the most extensive sets of ultrafast optical capabilities in one location in the world, with more than ten amplified laser systems capable of generating intense femtosecond pulses from X-ray to THz frequencies. These systems are used for ultrafast pump-probe spectroscopic characterization of materials ranging from strongly correlated systems (e.g., actinides and superconductors) to biological systems (e.g., DNA), as well as more advanced experiments including high power THz generation and ultrafast angle-resolved photoemissions spectroscopy. LUMOS also offers the ability to perform many ultrafast optical experiments in magnetic fields up to 8 T and time-integrated optical experiments including UV-VIS, FTIR, and Raman spectroscopy, all at temperatures down to 4 K.

CINT provides benefit to and derives benefit from other BES programs at both SNL and LANL. Specifically, there is strong synthesis and characterization synergy between the NPON thrust and BES programs, for example *Quantum Nanoelectronic Phenomena* by Lilly (SNL NEM thrust), Prasankumar (LANL, NPON thrust) and Pan (SNL), *Light-Matter Interaction Phenomena using Subwavelength Engineering of Material Properties* by Brener and Luk (SNL, NPON thrust), and *"Giant" Nanocrystal Quantum Dots: Controlling Charge Recombination Processes for High-Efficiency Solid-State Lighting* by Hollingsworth and Htoon. NPON scientists also had participated in a DOE EFRC: *Solid State Lighting*. Additionally, NPON researchers support the DARPA Quiness program using integrated nanophotonics for quantum communications and also support the DOE NETL TASQ program using integrated quantum optics for energy grid security. Working with Htoon and a U.S. lighting manufacturer, Hollingsworth is PI on an applied solid-state lighting program (EERE funded, CRADA supported: *Next-generation 'Giant' Quantum Dots: Performance-Engineered for Lighting*). Additionally, the Grand Challenge LDRD at SNL in quantum communications is led by CINT researchers (Camacho). Finally, the Grand Challenge LDRD at SNL entitled *Smart IR Sensors* aimed at developing tunable metasurfaces with IR semiconductor detectors is a great complement to the metamaterial activities that CINT is pursuing with its users. While these synergies exist, current and future projects within the NPON thrust, as described in this document, are distinct, in terms of scientific research topics and deliverables, from these complementary programs.

4.7 Distinguishing Characteristics of this Thrust

The Nanophotonics and Optical Nanomaterials Thrust consists of a robust combination of expertise and capabilities spanning synthesis, fabrication, advanced characterization, physics and integration of nanoscale materials and electromagnetic phenomena. World-leading and noteworthy expertise and capabilities include international leadership in developing core-shell non-blinking quantum dots; exceptional ultrafast spectroscopy capabilities paired with state-of-the art tools for microscopic imaging, spectroscopy, and dynamics measurements of single nanoelements and broadly tunable Raman probes; and internationally recognized innovation in the areas of active and all-delectric metamaterials. Collaborations with other thrusts at CINT, in particular with the Theory and Simulation Thrust and the Nanoscale Electronics and Mechanics Thrust, and with other programs, facilities and scientists at both Laboratories significantly benefit the scientific objectives of the NPON thrust. Further, this extensive and diverse array of resources for nanoscience research available to the NPON thrust enables its members to quickly reconfigure their research to respond to new challenges and remain at the forefront of the rapidly changing field of nanophotonics thereby providing optimal support to the user community.

5.0 Abstract

The Nanophotonics and Optical Nanomaterials thrust at the Center for Integrated Nanotechnologies (CINT) seeks to address the overall scientific challenge of understanding and controlling fundamental photonic, electronic, and magnetic interactions in nanostructured optical materials fabricated using both chemical and physical synthesis. The thrust includes ten scientific staff members, with associated postdocs and technologists, who utilize laboratory facilities at the CINT Core in Albuquerque, as well as the CINT Gateway in Los Alamos. Major thrust research areas include (1) chemical and physical synthesis of optical low-dimensional nanophotonic structures, (2) optical spectroscopy of low-dimensional nanostructures, and (3) metamaterials and nanoplasmonics. This thrust interacts directly with the other three CINT scientific thrusts to leverage expertise in related fields such as theoretical analysis of nanostructures, soft biomaterials, ultrafast spectroscopy of hard and soft nanomaterials, and cleanroom semiconductor fabrication and processing.

The scientific directions for this thrust for the next three years will follow these three main categories. Developments in these categories are expected to lead to rapid advances in light-capture applications (photovoltaics, photodetection, and radiation detection), light-emission applications (solid-state lighting, light-emitting diodes, lasers, quantum information processing, and so forth), and a new understanding of electromagnetic phenomena and solid-state excitations at the nanoscale.

6.0 Narrative

6.1 Background and Significance

The Center for Integrated Nanotechnologies (CINT) is a national user facility devoted to understanding the scientific principles that govern the design, performance, and integration of nanoscale materials and structures. Activities in CINT target exploration of the science of nanoscale integration, defined as

Assembling diverse nanoscale materials across length scales to design and achieve new properties and functionality.

Nanoscience integration extends from the synthesis and fabrication of individual nanoscale building blocks, possibly via combining different materials into specific heterostructures, and the assembly of these building blocks (often mediated by appropriate tailoring of surface chemistries or nanofabrication steps and surface structures across multiple length scales) to the generation of complex functional structures and systems. Such integration is the key to exploiting nanomaterials in applications and scientific investigations that can ultimately impact national and international needs in areas such as energy, environment, and security.

The common goal in the Nanophotonics and Optical Nanomaterials (NPON) thrust is to understand, control, and optimize the interaction of nanomaterials—from individual nanostructures to nanomaterials integrated at the nano-, micro-, and macroscales—with electromagnetic radiation. This is important both from a basic science perspective of understanding light-matter interactions at the nanoscale and for applications in areas as diverse as energy harvesting and storage, communications, sensing, and biology. For the NPON thrust, our current capabilities include the following:

Synthesis—Hollingsworth (solution-phase synthesis of semiconductor nanocrystal quantum dots [NQDs] and nanowires [NWs], their heterostructures, metal-semiconductor constructs, flow/automated synthesis, and integration using, e.g., dip-pen nanolithography), Ivanov (magnetic and semiconducting homogeneous and composite NQDs, 2-D semiconducting materials), Doorn (solution processing and covalent and noncovalent surface functionalization of carbon nanotubes).

Fabrication—Camacho, Brener, Luk (cleanroom techniques, e-beam lithography).

Characterization—Brener (metamaterials/plasmonics, ultrafast optics, photoluminescence [PL]), Doorn (Raman and photoluminescence spectroscopy of nanostructures, low-dimensional materials, and carbon nanotubes), Luk (micro-PL, time-resolved PL, plasmonics), Efimov (ultrafast measurements in fibers and plasmonics, infrared spectroscopy), Htoon (spatially resolved spectroscopy of semiconductor nanostructures), Prasankumar (ultrafast optical spectroscopy of nanostructures, correlated oxides, and metamaterials), Chen (metamaterials, THz-TDS, optical-pump THz-probe, THz-pump/THz-probe), Camacho (optical characterization, integrated optics).

NPON research deals with different aspects of the interactions of nanostructured materials with electromagnetic radiation across a wide range of frequencies and timescales, from terahertz (THz) to the ultraviolet and even X-rays and from femtosecond to steady state. Previous approaches to controlling light-matter interactions in nanoscale structures have relied on quantum-size effects. Size control, however, has limited applicability for tuning dynamical and nonlinear responses or inducing multifunctional behaviors. Alternative and complementary methods of controlling and tuning the optical properties of materials exist through the alteration of the physical environment in ways that have a strong influence on the optical density of states or in rates of energy transfer. Examples are (1) the development of complex metal-semiconductor nanoparticles, such as core-shell metal-semiconductors, semiconductor-metal nanowire (NW) constructs, or integration of luminescent nanoparticles with fabricated plasmonic structures and nanoresonators; (2) the integration of quantum dots with photonic crystal cavities or structured metals; (3) metamaterials that overlap a frequency range of some fundamental excitation of the optical material or that allow unique ways to alter the permittivity and/or permeability in 1, 2, or 3 dimensions; (4) nanostructured metal oxides that combine different functionalities (e.g., superconducting, ferromagnetic, and/or ferroelectric) in a single device; and (5) chemically stable dopant-induced optical states or intertube interactions inducing new excitonic forms in carbon nanotubes of selected structure. Such a focus on targeting emergent optical phenomena through multiple materials interactions is strongly aligned with our forward-looking strategy for creating hybrid materials interactions for the generation and manipulation of light. Efforts will also harness a push toward methods for incorporating and organizing quantum-size nanostructures into arbitrary 2D and 3D architectures via top-down, soft, and bioinspired approaches.

As part of these general directions, we will continue our quest for multicomponent nanostructures as building blocks for new types of optical metamaterials. We will design them in such a way that they respond resonantly to either the electric or magnetic component of the field, or both. We will utilize known and novel methods of directed assembly (using growth templates defined, e.g., lithographically or colloidally) to process them into ordered structures that target certain wavelength ranges from the THz to the visible. Sub-wavelength structuring of novel composite materials has shown the ability to manipulate, control, emit, and detect electromagnetic radiation. Efforts include integration of a variety of condensed-matter systems and heterostructures with metamaterials, ultra-thin planar metamaterials, active metamaterials, and ultrafast optical switching in these materials.

We will continue comprehensive studies of low-dimensional structures, including carbon nanotubes (CNTs), semiconductor quantum dots (QDs) and NWs. Control and even enhancement of intrinsic behaviors now accessible in single-chirality CNT samples will be pursued via surface chemistry, novel doping approaches, and tailoring of intertube and multi-component interactions in optically active matrices. A key aspect will be exploiting our powerful suite of single-tube and ensemble-level photoluminescence, Raman, and time-resolved spectroscopies. Paired with new methods for spatially correlated structure and composition analysis, this suite also will be applied to CINT-developed giant QDs (g-QDs) to inform rational synthesis of new compositions for individual and interacting g-QD structures, accessed via unique automated synthesis and dynamic assembly strategies. Targeted behaviors include expanding the accessible range of g-QD emission wavelengths and control of quantum emission. A continuum of photonic response from classical through multi-exciton (g-QDs) to single-photon emission (CNTs) will be enabled by ultrafast superconducting NW detectors for photon counting and correlation measurements and will allow a coordinated push towards quantum optics studies for quantum information needs. Additionally, efforts will target 1D quantum-confined structures synthesized using solution-based chemical approaches that provide access to ultra-small-diameter and uniquely heterostructured NWs. These structures remain largely unexplored compared with their epitaxially grown counterparts. Synthetic advances will rely on our customized microfluidic reactor for “flow” solution-liquid-solid (flow-SLS) growth, which has permitted the facile synthesis of axially heterostructured NWs and unprecedented mechanistic studies of solution growth.

While the work outlined above covers a diverse group of materials and devices, it is unified by the single underlying goal of understanding, controlling, and optimizing the interactions of these materials with electromagnetic radiation. As a result of this work, we expect to establish design principles for light-matter interactions in optical nanomaterials . This fundamental knowledge will be a valuable resource for the development of novel optical nanomaterials as well as new approaches for the manipulation of photons (e.g., necessary for optical communication and information processing) and the conversion of photons to other types of excitations and the reverse processes (e.g., in photovoltaics, solid-state lighting, and plasmonic circuitry). Most of the work proposed and ongoing in our thrust requires integration of nanomaterials and nanofabrication in order to achieve the desired functionality. Scientists in the NPON thrust will perform this work in partnership with members of the CINT user community, along with key members of other CINT thrusts. In particular, NPON has demonstrated remarkable success at harnessing such cross-thrust interactions among principal investigators (PIs) and postdocs to establish those working in the NPON thrust as leaders in developing and modeling active and multifunctional nanoplasmonic and all-dielectric metamaterials. Leadership in NW generation and integration for energy efficiency, harvesting, and storage, has grown out of such highly collaborative interactions as well.

In the sections that follow, we highlight our previous work in these areas, followed by detailed descriptions of our plans for the next three years. *As most of our activities are and will be based on user interactions, specific user projects are referenced where appropriate, either directly in the text (highlighted by User Project number) or, where possible, tied to specific publications, listed in Section 7.1.*

6.2 Progress Report

6.2.1 Synthesis, Processing, and Manipulation of Low-Dimensional Nanostructures

Exploration and Transformation of Indirect-to-Direct Bandgap Transitions: Nanocrystalline Ge and Si (Ivanov)

Silicon and germanium are the most crucial elements in the semiconductor industry, but their use in light-absorbing applications is limited due to their indirect band gaps in bulk. Si and Ge have potential for conversion to direct gap materials by alloying with Sn, thereby rendering them more highly light absorbing. However, the large lattice strain and low solubility of Sn in Ge and Si makes it challenging to obtain such alloys in bulk. Nonetheless, given the ability of materials at nanoscale to relax large lattice strains, combined with the use of strategic precursor molecules, we have achieved the synthesis of Sn_xGe_{1-x} alloy nanocrystals (NCs) with full compositional range (0.95 > x > 0) [1]. We have confirmed the homogeneous distribution of elements within alloy nanocrystals and conducted mechanistic/computational studies of the material formation. Absorption spectroscopy of NCs of varying composition demonstrated an increased molar absorptivity (up to a 10-fold increase) of the alloy compared with the pure Ge NCs (Figure 1), directly indicating a transition to direct band gap behavior with increasing Sn content. Mechanistic insights gained from the study of Sn-Ge nanoalloy formation allowed introducing Si into the alloy composition as well, leading to the synthesis of ternary SiGeSn nanoalloys. These new materials have improved potential for roles in light harvesting and as replacement electrode materials in Li-ion batteries.

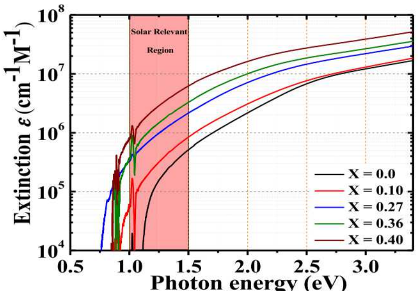

Figure 1. Extinction coefficient spectra of 9 nm Sn_xGe_{1-x} nanocrystals [1].

Indirect-to-Direct Bandgap Transitions: Layered 2D Materials (Ivanov)

Layered chalcogenide materials have been attracting vast interest due to their thickness-dependent optical and electrical properties, with indirect-to-direct transitions occurring at the single-layer limit. Beyond the current focus on binary 2D chalcogenides, MoS_2-based ternary-layered chalcogenides are potentially more advantageous because, in addition to thickness-dependent quantum confinement effects, they can provide additional degrees of freedom for tuning electrical and optical properties. Of particular interest are Cu_2ME_4 (M = Mo, or W; E = S, or Se) due to their structural similarity to binary "parents" ME_2 (M = Mo, or W; E = S, or Se). We have initiated research on the ternary material's electronic properties and have performed electronic structure calculations on Cu_2MoS_4 with different layer thicknesses using density functional theory (DFT) (U2014A0029). To date, we have demonstrated that, in contrast to MoS_2, introduction of copper into the structure renders the material to be an indirect gap semiconductor even in the monolayer morphology. The effects of different transition metal ions instead of copper and of Mo and S replacement by W and Se, respectively, on electronic properties are currently evaluated [2,3]. In addition, we have synthesized nanoplates of Cu_2MoS_4 with different thicknesses and studied their electrochemical properties for promoting the hydrogen evolution reaction (HER).

New Semiconductor and Hybrid Semconductor-Metal Optical Emitters (Hollingsworth)

CINT's internationally recognized program in nanocrystalline QD light emitters is founded on our development of core-shell g-QDs characterized by strongly suppressed fluorescence blinking, photobleaching, and nonradiative Auger recombination. We are now extending the g-QD motif to new compositions and functionality via a rational *materials-design strategy* aimed at replicating and extending g-QD properties [4,5]. Theoretical modeling of shell thickness and core diameter dependencies for electron-hole overlap and bandgap energy (E_g) has guided synthesis of two underdeveloped core/shell systems: CdSe/ZnSe and ZnSe/CdS g-QDs. By developing new synthetic strategies, we overcame challenges of competitive alloying and cation exchange to obtain the desired structures, with excellent agreement with predicted optical properties [6,7]. By full-parameter control of relative core/shell thicknesses and associated hole physics, we have demonstrated control over biexciton quantum yields [8] and are extending emission wavelengths into the yellow and green range, with strategies to extend to blue wavelengths. Functionality of the g-QDs has been further extended via integration with metal shells separated from the QDs by dielectric spacers. The g-QD behavior is retained but is now paired with a metal's ability to be photothermally heated, with the g-QD acting as an "onboard" nanoscale thermometer [9]. Finally, through external user projects the new g-QD systems are enabling study of previously inaccessible behaviors, including multicarrier radiative and nonradiative processes [10].

Advancing Colloidal Synthesis and Integration Methods for Controlled Complexity in Structure and Function (Hollingsworth)

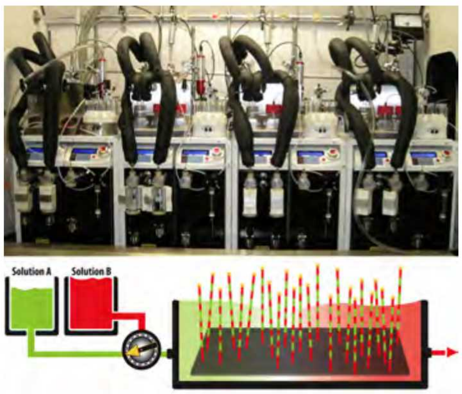

Figure 2. Illustration of automated reactor system for solution-phase synthesis of nanowires and quantum dots.

We transformed the SLS method of semiconductor nanowire (SC-NW) synthesis into a flow-enabled technique (Figure 2), with the resulting synthetic control affording unprecedented mechanistic insight and a platform for designed synthesis of technologically significant axially heterostructured SC-NWs [11]. Furthermore, we have installed an *automated reactor system* (Figure 2) that combines software-controlled synthesis with *in situ* real-time diagnostics and automated sampling for rapid exploration of synthetic phase space in the context of multi-step nanomaterials synthesis for discovery, optimization, and scale-up (manuscript in preparation). In addition to developments in colloidal synthesis techniques, we have used both conventional (lithography and drop-deposition) [12–15] and nonconventional (dip-pen nanolithography [DPN]) integration strategies to create and study hybrid photonic-plasmonic nano-meso structures. With *CINT external users*, we have investigated g-QD/optical antenna couples created by scanning-probe-assisted methods [16,17] or by our own pursuit of advanced DPN strategies for directly "writing" nanocrystal "inks" onto nanosize 3D substrates. The latter is currently being applied to direct writing of novel g-QD/nanowire-waveguide composite structures toward control over single-photon source properties such as radiative rate, directionality, and photon-collection efficiency.

0D and 1D Optical Nanomaterials for Energy Harvesting, Lighting, and Biology (Hollingsworth)

By developing a "geometry-independent" integration approach for fabricating nanocrystal-sensitized solar cells, we were able to compare 0D QDs with 1D NWs as the "dye" component for sensitizing TiO_2-based solar cells [18]. Unexpectedly, for equivalent nanocrystal masses, NW devices yielded higher power-conversion efficiencies, resulting from both enhanced light-harvesting efficiencies and internal quantum efficiencies that are more than double those obtained for QD devices—direct consequences of the NW anisotropy. With a CINT external user, we also explored the utility of NWs as building blocks for thermoelectric devices [19]. In contrast to energy-harvesting applications, light-emission applications benefit from 0D quantum confinement properties. Here, we explored g-QDs giving nearly ideal characteristics for down-conversion phosphor applications in lighting with unprecedented near-unity down-conversion efficiency [20]. In biology, nonblinking g-QDs were exploited to study IgE-FcεRI receptor dynamics in live cells using CINT's confocal-based 3D single-photon-tracking microscope. Importantly, the 7-fold increase in IgE-FcεRI tracking duration afforded by the g-QDs (compared with commercial QDs) allowed the observation of multiple changes in diffusion rates of individual receptors occurring on long (>1 min) time scales (>1 min). Nonblinking g-QDs are thus likely to become important tools in other live-cell studies, especially in cases where cellular dynamics occur on timescales of several minutes [21,22].

Surface Chemistry, Separations, and Synthesis of Carbon Nanomaterials (Doorn)

We continue to demonstrate PL as a sensitive probe of CNT surface structure, having established the dynamic behavior of surfactants at the CNT surface and the role of surface disorder in determining PL efficiencies and lifetimes [23]. Such understanding has been a critical aspect of our recent establishment of a new route towards CNT separations based on aqueous two-phase extraction [24–26]. By probing the mechanism of these new separations (in which nanotube chirality was shown to determine the relative hydrophobicity of surface structures by influencing mixed-micelle compositions and structure), we devised a highly efficient, rapid (~5 min) and scalable, one-step process for separations of target CNT structures [24]. Further refinement showed this approach as a means to eliminate the need for expensive and time-consuming ultracentrifugation in CNT processing—a major advance [25]. The high volume and optically dense single chirality samples now available through the aqueous two-phase (ATP) approach are critical for advancing our efforts in fundamental CNT spectroscopies and a new push into covalent doping chemistry. Such doping holds tremendous potential to enhance PL emission [27,28] and open applications in quantum information [29]. We have established a capability for solution doping of a wide range of CNT chiralities with both oxygen dopants and synthetically tunable aryl diazonium species. A new process developed in our lab provides extremely fine control of doping extent—even to the solitary dopant level (Figure 3) [30]. Paired with the unique small-diameter chiralities we can isolate, this new capability has become a strong draw for several new users (~6 related user projects). Finally, we have reconfigured our chemical vapor deposition (CVD) growth furnace for efficient production of large area graphene, which is allowing pursuit of new directions in graphene-based heterostructures with g-QDs [12], nanowires, and complex oxide thin films.

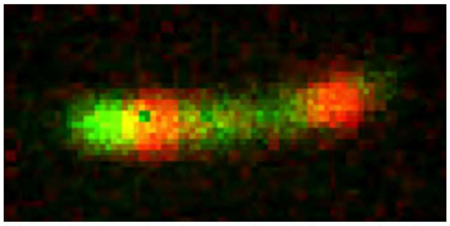

Figure 3. Correlated two-color PL image showing emission from spatially isolated (solitary) dopant sites (orange) in relation to normal exciton emission (green) from a single carbon nanotube.

6.2.2 Optical Spectroscopy of Low-Dimensional Nanostructures

<u>Development of Novel Spectroscopic Capabilities (Htoon, Doorn, Prasankumar, Efimov)</u>

A particular strength of CINT is the close interaction between capabilities for materials generation and optical characterization. New materials behaviors drive development of new spectroscopic capability in the thrust. As one example, a user project (U2014B0001) requiring correlation of spectroscopic and structural properties of individual g-QDs is driving development of an approach to perform advanced single nanostructure spectroscopies (Raman, PL, time-resolved PL, photon correlation spectroscopy, etc.) and high-resolution scanning electron microscopy (SEM) and transmission electron microscopy (TEM) on the same set of individual nanoscale materials. Figure 4 demonstrates the first direct correlation of PL time trace, decay curve, and 2nd-order photon correlation function with the atomic composition of the same giant nanocrystal quantum dot (g-NQD). A direct approach to simultaneous correlated two-color (at visible and near-IR wavelengths) PL imaging of nanostructures has also been established [30], allowing studies of multicolor emitters such as covalently doped carbon nanotubes and emerging compositions in g-QDs. We have also integrated a four-channel, superconducting nanowire, single-photon detector into the existing single-nanostructure optical spectroscopy system. We can now perform Hanbury Brown Twiss [29] and Hong-Ou-Mandel quantum optics experiments on individual nanostructures emitting in the 1.0- to 1.5-micron wavelength range. Only a few groups in the US have demonstrated such a capability. Additionally, a novel fs pump, second-harmonic generation (SHG) probe technique for probing coupled multiferroic behaviors in oxide heterostructures [31] has been added to our world-class ultrafast spectroscopy capabilities. CINT ultrafast capability was also harnessed for establishing a new surface-enhanced coherent anti-Stokes Raman [SECARS] microscopy system that exploits gold nanopyramids as active substrates well suited for probing solution-based monolayers, bio membranes, and other soft and complex materials. Finally, a custom Z-scan approach for measuring Kerr nonlinearities and two-photon absorption was established in support of a startup firm (EigenChem) to develop nonlinear photonic devices.

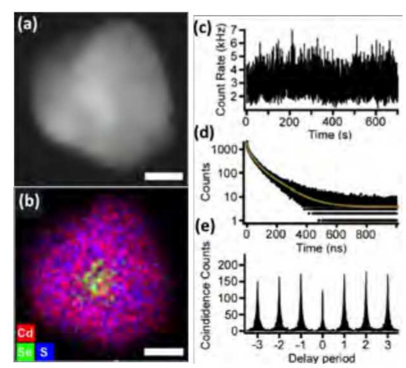

Figure 4. High resolution TEM image (a), scanning TEM energy dispersive X-ray maps (b), PL time trace (c), PL decay curve (d), and $g^{(2)}$ trace of a single g-QD.

Understanding of Fundamental and Quantum Optical Processes in g-QDs and Carbon Nanotubes (Htoon, Doorn)

Towards control of photon conversion pathways in g-QDs, we investigated the influence of core size, shell thickness, composition, and shape of confinement potentials. The studies (a) revealed that g-NQD core size is an effective tuning parameter toward higher biexciton quantum yield (QY) [8], (b) identified InP/CdS as the first NQD capable of "on-demand" single-photon emission in the near-IR spectral range [32], (c) demonstrated that blinking suppression cannot be achieved in CdSe/ZnSe g-QDs due to asymmetric band alignments, opposite that of CdSe/CdS g-QDs [7], and (d) illuminated scaling of Auger recombination rates for eight distinct multi-exciton and charged-exciton states [10].

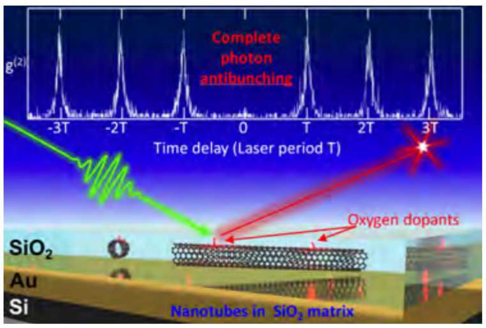

Figure 5. Doped CNT encapsulated in SiO_2 matrix (bottom) and $g^{(2)}$ trace (top) showing complete photon antibunching (single-photon emission).

Extensive studies of covalently doped CNTs provided the first detailed understanding of the origins of the dopant-state PL emission [30,33]. Low-temperature (low-T) spectroscopy, paired with quantum chemistry results, defined the electronic structure and chemical functionality of the dopant sites [33]. Combined with correlated PL imaging data [30], a picture emerges of dopant emission arising from exciton localization to a region <4 nm around the dopant site. Low-T PL correlation spectroscopy we performed on undoped single tubes showed that exactly such localization is a prerequisite for single-photon emission from CNTs [34]. Discovery of a solid-state doping approach [35] equivalent to solution processes allowed us to demonstrate for the first time (Figure 5) single-photon emission from CNTs at room temperature [29] and provides the first route to room-temperature quantum emitters in the telecom wavelength range that are fully compatible for integration into electrically driven devices. Theoretical modeling of dopant-state blinking discovered in solution-doped CNTs points to future strategies for design of new dopants for optimizing single-photon emission behavior [30].

Plasmonic Manipulation of Fundamental and Quantum Optical Processes (Htoon, Doorn, Efimov)

Toward achieving extrinsic control of emission processes, we coupled g-QDs and CNTs to a wide variety of plasmonic nanostructures. We showed plasmonic fields strongly influence spectral diffusion of PL emission wavelengths via exciton localization [36] and theoretically modeled the associated reorientation of the CNT emission pattern, controlled by manipulating the exciton-plasmon coherences [37]. Our study of g-QD-graphene monolayer hybrids revealed that a charged g-QD can induce the formation of a charge puddle capable of supporting a new type of plasmon mode at the g-QD-graphene interface [12]. This new plasmon mode is formed directly underneath the g-NQD, providing a solution to a general problem of quantum emitter-plasmonic cavity alignment that has hindered realization of strong plasmon-exciton coupling, thus opening a new route to quantum plasmonics. QD interactions with other 2D materials (MoS_2) were also explored, with time-resolved exciton dynamics and energy transfer being modulated via electrical control to demonstrate up to 75% energy transfer efficiency from QDs to MoS_2 [38]. Plasmons in graphene nanoribbon devices were also studied with FTIR microscopy as a function of substrate and gate bias. In addition to observation of plasmon-phonon hybridization, rich surface/interface charge dynamics were found and are the subject of continuing study.

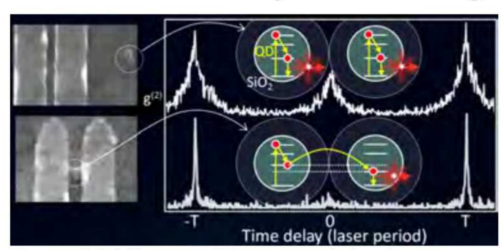

Figure 6. While two g-QDs not coupled to the antenna behave as two independent emitters (top), two g-QDs trapped in the gap bar exhibiting single-photon emission indicating the formation of quantum dot molecules (bottom).

In pairing a range of lithographically patterned antennae with g-QDs, we demonstrated that antennae plasmonic fields have no effect on Auger recombination of biexcitons [13] and that fringe fields of metal-dielectric-metal nanopatch antennae can provide up to a factor of 15 enhancement to the radiative recombination rate of the g-QD [15]. Effects on g-QD pairs, revealed for the first time, were especially intriguing. Plasmonic-induced coupling between two g-QDs forces them to behave as a single quantum emitter (Figure 6), indicating the coupled dots can be considered as "quantum dot molecules" [14]. Such quantum dot molecules may be the key building blocks for solid-state quantum computation architectures and provide a route to such quantum photonic/plasmonic devices as single-photon transistors and routers, needed for the removal of optical-electronic-optical conversion bottlenecks in quantum and classical communication networks.

Probing Phonons in Carbon Nanomaterials (CNTs, Graphene and Low-Dimensional Analogues) (Doorn)
Prominent non-Condon effects in Raman excitation profiles of multiple CNT phonon modes, discovered by us in semiconducting CNTs [39], were shown to be a general behavior also appearing in metallic CNTs [40]. Theory demonstrates the behavior originates in the excitonic nature of CNT transitions. ATP-generated single-chirality metallic samples also allowed the first probing of structural dependences in high-frequency phonons and produced the first experimental evidence for a new form of Kohn anomaly [41]. Other user-inspired Raman studies provided a baseline for behaviors observed in coherent phonon response [42], revealed intrinsic graphene lineshapes [43], and led to studies of "elemental" CNT molecules (cycloparaphenylenes, [CPPs]) that established theoretical models for the phonon-driven exciton localization that underlies all CPP optical behaviors [44–46].

Ultrafast Processes in Complex Oxides and Oxide Heterostructures (Prasankumar)
Ultrafast photoinduced phase transitions could revolutionize data-storage and telecommunications technologies. In quantum phase-changing materials (PCMs), different degrees of freedom interact cooperatively to modify macroscopic electrical and optical properties, but relatively little is known about the ultrafast dynamics of nanostructured PCMs when interfaced with other classes of materials. In collaboration with CINT users at Vanderbilt University and the University of Alabama-Birmingham, we demonstrated how a mesh of gold nanoparticles, acting as a plasmonic photocathode, induces an ultrafast phase transition in nanostructured vanadium dioxide (VO_2), a canonical phase transition material, when illuminated by a femtosecond pulse [47]. Hot electrons created by optical excitation of the surface plasmon resonance in the gold nanomesh are injected across the Au/VO_2 interface to induce a sub-picosecond phase transformation in VO_2, with thresholds a factor of 5 lower than in pristine VO_2. This opens up the possibility of designing hybrid nanostructures with unique nonequilibrium properties for all-optical nanophotonic devices with optimizable switching thresholds.

Multiferroic materials have attracted much attention due to their potential for controlling magnetism with an electric field and ferroelectricity with a magnetic field. The mechanisms and timescales governing the coupling between electric and magnetic order (magnetoelectric [ME] coupling) in multiferroic materials are not well known. This has made it difficult to increase the strength and operating temperature of ME coupling in multiferroic devices, limiting their potential applications. To tackle this problem, we used ultrafast optical spectroscopy to study an oxide heterostructure consisting of a ferroelectric layer grown on top of a ferromagnetic layer [31]. Femtosecond photoexcitation modifies magnetic order in the ferromagnetic FM layer and changes the distance between its atoms through magnetostriction. This in turn changes the distance between atoms in the ferroelectric FE layer, which modifies its ferroelectricity, which can be measured through second harmonic generation of another time-delayed optical pulse (Figure 7). We found that the timescale on which this effect occurs is governed by spin-lattice relaxation in the FM layer within tens of picoseconds. These results provide important insight into the mechanisms underlying ME coupling in artificial multiferroic composites and show that optical pulses can be used to control the response on ultrafast timescales.

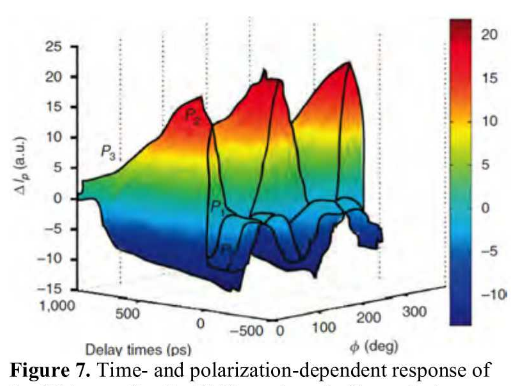

Figure 7. Time- and polarization-dependent response of the FE layer after the FM layer is optically excited.

6.2.3 Integrated Quantum Photonic and Optomechanical Circuits (Camacho)

CINT has introduced the ability to design, fabricate, and test microphotonic and phononic devices [48]. An entirely new lab facility has been built up over the past 2 years to support this effort. This capability has attracted several new users from top universities around the world and has already led to some exciting new results, with two manuscripts under review at high-profile journals [49,50]. For example, in collaboration with researchers at MIT (U2014B0007), we are implementing high-efficiency, on-chip arrays of single-photon sources and detectors. With the University of Bristol (U2014B0052), we are constructing multiphoton sources for quantum cluster state generation, and with Harvard University (C2015B0001), we have demonstrated single-photon transistors using negatively charged silicon vacancy centers in diamond [49]. In addition, with users from Sandia National Laboratories (RA2014A0013), we have fabricated optical devices in LiNBO3 capable of very efficient parametric upconversion and downconversion. In order to support and attract users, we have also developed several unique tools. One of these is the ability to attach fiber arrays to chip-scale waveguide arrays with >90% transmission efficiency [50] using active alignment. This best-ever result allows us to extract optical signals with very high signal-to-noise ratios and preserve quantum entanglement. We also now have a new prototype process capable of achieving similar results using passive alignment, allowing CINT users to couple light into and out of chips at their home institutions as well.

6.2.4 Passive and Active Metasurfaces (Brener, Chen, Luk)

Two-dimensional metamaterials, or metasurfaces consisting of single-layer or few-layer stacks of resonator arrays with subwavelength thickness, can overcome many challenges (e.g., high loss, strong dispersion, and complicated fabrication) encountered in bulk metamaterials. The planar metasurface arrangement facilitate the integration of functional materials for active control and enhanced light-matter interactions, as well as novel device architectures for optical functionality.

All Dielectric Metasurfaces

Almost all of the functionality of metallic metamaterials and metasurfaces can be obtained with high-index transparent dielectrics by tailoring magnetic and electric Mie resonances and their corresponding effective medium permittivities and permeabilities [51]. The application of this approach for metamaterials at optical frequencies started just a few years ago, and CINT has been at the forefront of this research. Using micron-sized cubes of Tellurium on a low-index BaF_2 substrate and an ultrafast phase-stabilized time-domain spectrometer, we demonstrated optical magnetism in the thermal infrared [52–54] (Figure 8(i)). Scaling all-dielectric metasurfaces to the near-infrared is possible with high-index semiconductors operating at energies below their bandgap (i.e., silicon, germanium, etc.). Through several user projects with the Australian National University [ANU] and the University of Texas-Austin (C2015B0053, C2013B0048 and U2012A0053, C2015A0087, C2014B0047) we have used silicon-based dielectric metasurfaces to (1) alter the directionality of optical scattering for passive metasurfaces [55] and emitters coupled to metasurfaces [56], (2) design Huygens metasurfaces that allow a large optical phase shift while maintaining unity transmission [57,58], (3) create chiral structures that operate in the mid-infrared [59], and (4) investigate a number of Fano resonant structures using coupling between dielectric resonators in an oligomer geometry [60]; see Figure 8, (ii) and (iii)). Lately, our users from ANU and Moscow State (C2015B0053) have discovered that third harmonic generation gets strongly enhanced when the pump overlaps with the magnetic dipole resonance of silicon dielectric resonators [61]; the ability to utilize different Mie modes to tailor the effective nonlinear response of metasurfaces is a new direction in the nanophotonics community and we plan to investigate more in the next few years.

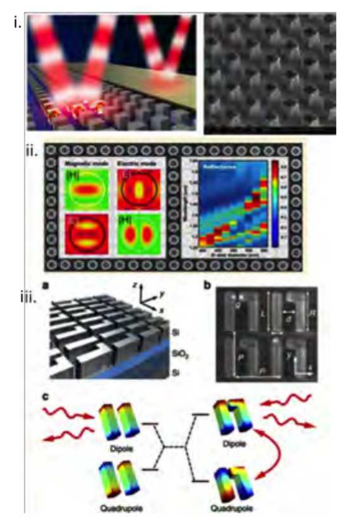

Figure 8. (i) Schematic diagram and SEM of optical magnetic mirror made from Tellurium cubes (~1.5 um^3) patterned on a BaF_2 substrate. (ii) Silicon metasurface consisting of nanocylinders patterned on a Si wafer with a SiO_2 spacer, and their corresponding magnetic and electric dipole modes; right figure shows transmission data as a function of dimensional scaling. [55] (iii) Another all-Si metasurface consisting of arrays of coupled Si nanoantennas that show chiral response and very sharp Fano resonances. [59]

Metallic Metasurfaces

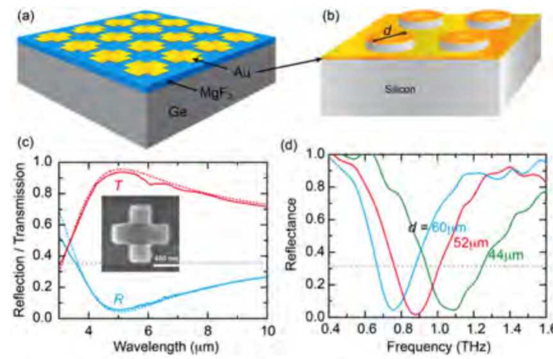

Figure 9. (a,b) Schematics of metasurface antireflection coatings. (c,d) Measured reflectance (and transmittance) for structures in (a and b), respectively. Inset to (c): SEM image of a metasurface unit cell in (a). Horizontal dashed gray lines: reflectance from a bare substrate.

Previously, an innovative bilayer metal-dielectric-metal metasurface structure functioning as antireflection coating was first demonstrated in CINT [62]. This accomplishment has resulted in multiple user projects with a goal of developing simplified metasurface structures, including a single-layer metal metasurface on top of a thin dielectric spacer [63] (see Figure 9, a and b) (U2014A0067); and the use of an array of metal-coated silicon cylinders [64] (see Figure 7, c and d) (U2013B0119); and cross pillars operating at terahertz and mid-infrared frequencies. Additional unique advantages of such metasurface antireflection coatings include the deep subwavelength thickness and no requirement of index match from the dielectric materials being used, which also attracted another now-on-going user project in applying metasurface antireflection coatings to enable low-T terahertz nonlinear experiments in strontium titanate, in which the ultrahigh refractive would have prevented any penetration of terahertz waves to the strontium titanate crystal (U2015A0057). On the other hand, we are able to arbitrarily control the reflection phase while keeping the reflection amplitude high (i.e., low absorption). A random distribution of scattering (reflection) phase from an array of these units has resulted in the elimination of specular reflection from a smooth surface, and we have been able to create desirable scattering patterns by using coding and digital metasurfaces [65].

Complementary perfect absorbers are also being developed in CINT, based on the transition of materials properties from dielectric to metallic at particular frequencies, at which their permittivity is near zero (epsilon-near-zero [ENZ]). A deeply subwavelength-thick unpatterned film of such a material will exhibit a large field enhancement in the vicinity of this frequency. Concurrently, the optical mode of this film can be impedance matched to free-space, enabling perfect absorption. We experimentally demonstrated this condition in the form of complete absorption in a deeply subwavelength (lambda/50) indium tin oxide (ITO) film [66]. The perfect absorption is a result of coupling the external field to the ENZ mode. Field enhancement can be quite dramatic for low-loss ENZ materials. Although ITO is not an exceptionally low-loss material, we have demonstrated that a field enhancement of 4.5 in ITO can dramatically increase the third harmonic generation yield by nearly 4 orders of magnitude [67]. Since the ENZ frequency is dictated by the dopant concentration of tin in In_2O_3, this frequency can be tuned by dopant concentration or material host. This tunable enhanced absorption/emission property was demonstrated in the infrared wavelengths using III-V semiconductors [68].

In CINT we have explored novel metasurface structures for a variety of functionalities; in particular, we pioneered the few-layer metasurface structures for polarization manipulation and wavefront shaping [69]. This accomplishment paves the way towards the development of next-generation high-efficiency flat optical components to meet the increasingly demanding requirements in integrated photonics. In another series of work, by taking advantage of the Pancharatnam-Berry phase caused by the orientation of anisotropic resonators, we have accomplished simultaneous control of polarization and phase for anomalous refraction and the creation of radially polarized beams [70], as well as for the realization of a metasurface half-wave plate operating in the near-infrared wavelength range [71].

Active Metasurfaces: Tunable Behavior and Studies of Light-Matter Interaction

Active control of metamaterials and metasurfaces extends their exotic passive properties by allowing fine resonance tuning to adapt the operational conditions and enabling a switchable resonant response for signal modulation in communication and imaging. We have continued our leadership in this area by accomplishing (1) an ultra-broadband terahertz metasurface modulator through photoexcitation of the integrated silicon using near infrared light, which results in highly efficient switching between high and low transmission caused by the transition from a dipole resonance to a wire-grating filtering [72] (U2012B0061, C2015A0046); (2) active control of electromagnetically induced transparency analogues in terahertz metamaterials through using a similar photoexcitation approach [73] (UC2010A954); (3) an electrically driven THz metasurface diffractive modulator with more than 20 dB of dynamic range [74] (C2012A0030, C2013B0008); and (4) tunable and nonlinear high-temperature superconducting metasurfaces that are also of fundamental importance in investigating the dynamic and nonlinear process in these materials [75,76] (U2010A989, C2013A0122).

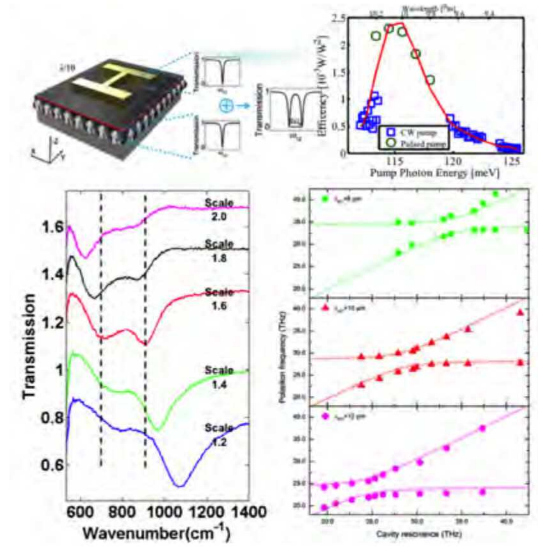

Figure 10. (top left) Schematic of a metallic metamaterial resonator coupled to a dipole active transition, an ENZ mode, or an intersubband transition in a quantum well (QW). (top right) Transmission spectra as a function of resonator scaling showing strong coupling to an ENZ mode [78]. (bottom left) Same as (top right) but for an intersubband transition in an InGaAs QW and for three different samples [81]. (bottom right) SHG obtained from a metasurface coupled to a resonant chi(2) designed in a QW. [84]

The spectral response of planar metamaterials is exquisitely sensitive to the local dielectric environment. Materials that exhibit strong dipole transitions when placed in close proximity to the resonator traces lead to large Rabi splittings in the spectral response, indicative of strong coupling phenomena. We have observed such phenomena when coupling metasurfaces to ENZ modes [77–79] (U2015B0045) and intersubband transitions in quantum wells, from the near IR [80] to the thermal infrared [81,82]. Intersubband transitions can be designed with a large sensitivity to an applied bias, and this phenomenon can be used for effective voltage-tunable strong coupling behavior [83]. In addition to strong coupling behavior, metamaterials coupled to intersubband transitions exhibit very high second-order nonlinear response, when a resonant chi(2) is designed in the semiconductor quantum wells using intersubband transitions. The strong fields produced in the near-field region of the metallic resonators lift the in-plane selection rules for intersubband transitions and lead to an "effective" nonlinearity that is higher by orders of magnitude when compared with the semiconductor sample alone [84,85]. Since each resonator in the metasurface acts as a new point source of light at a new wavelength, complex arrangements of resonator geometries with different phase relationships can be created for the manipulation of the emitted second harmonic radiation. (U2014B0054) Figure 10 highlights some of our recent results.

6.3 Future Work

6.3.1 Synthesis, Processing, and Manipulation of Low-Dimensional Nanostructures

Alloyed Nanoparticles and 2D Layered Materials for Energy Conversion and Storage (Ivanov)

We will continue our work with both SiGeSn alloys and layered 2D Cu_2ME_4 systems, as both systems clearly demonstrate the potential for optical and electrochemical applications. The latter set of applications is oriented toward energy-generating and storing applications. The GeSn and SiGeSn nanoalloys are promising materials for use as anodes in metal ion batteries as they are more rheologically robust toward the lattice expansion/contraction that occurs during the charge/discharge cycles. The Cu-M-E systems (E = S or Se and expanded with M = Mo, W, Sb, or Bi) are considered for use in (1) photovoltaic applications, as it has been predicted that some of these formulations will have a direct energy gap in the solar-relevant region, and (2) as an active medium in supercapacitors. Due to the 2D layered structure, with relatively large separation between layers, it has already been demonstrated that the Cu-Sb-S system can be intercolated with alkali metal ions during the charge cycle of a supercapacitor. These materials have also demonstrated high charge density upon charging together with robust behavior during multiple charge/discharge cycles. Finally, in order to advance the development of new narrow-gap semiconductors outside of the area of lead chalcogenides, we will focus our efforts on the synthesis of SnTe, which has additional advantages, including being a lower-toxicity and higher-stability nanomaterial with the optical band gap of 0.18 eV and very large exciton Bohr radius of ~100 nm (U2015B0047).

Synthesis-Structure-Function Correlations: Rapid Evolution of new Complex Functional Optical Nanomaterials (Hollingsworth, Htoon)

New capabilities in flow-enabled synthesis or automated synthesis with *in situ* diagnostics, rapid structural/optical characterization, and correlated structure/optical characterization are being developed in a coordinated fashion to be implemented for the discovery, elucidation, and optimization of advanced optical nanomaterials. By customizing a microfluidic flow reactor, we have established a new approach for solution-based NW synthesis called flow-SLS growth [11], which has permitted the facile fabrication of axially heterostructured NWs and unprecedented mechanistic investigations. We propose to extend this novel technique to synthesize technologically relevant nanodisk-in-nanowire quantum emitters (see below). Our new automation capability for complex/multi-step nanomaterials synthesis affords rapid exploration of synthetic phase space, enabling execution of sophisticated combinatorial-style workflows. Combined with *in situ* diagnostics for assessing real-time solution turbidity and nanomaterial absorption and PL, the automated approach we have developed will enable us to quickly and directly correlate specific reaction steps with an outcome, e.g., growth in the structure via absorption shifts, modification of an interface or nanoparticle surface chemistry via PL intensity changes, change in electronic band structure via magnitude of PL shifts, and evolution of dipole moment via fluctuations in particle-particle associations assessed in turbidity measurements. The rapid feedback provided by *in situ* characterizations will enable the researcher to stop workflows that are proceeding in unproductive directions or to modify the process midstream.

For workflows that are brought to completion, the resulting reaction products will initially be assessed by rapid-screening tools to down-select the most promising candidates for complete characterization. The rapid-characterization suite includes a desktop TEM (for size and shape assessment), a Nanosight optical microscope (bright/dark fraction assessment), micro-volume spectrophotometer and fluorospectrometer (NanoDrop, Inc.), desktop time-correlated single photon counting [TCSPC] lifetime system with temperature-controlled sample holder (Horiba DeltaFlex), and a home-built CCD detector/laser/software setup for ultra-widefield optical microscopy (>100 x 100 μm) for statistically relevant sampling of single-nanoparticle PL properties 4-fold faster than standard setups.

Finally, as a critical complement to the above synthesis/assessment strategies, we will pursue a new ability to directly correlate single-nanoparticle-level functionalities with single-nanoparticle structure and composition as a key enabling insight for directing future synthesis workflows and nanomaterials structure targeting (as seen in Figures 4 and 11). With CINT users and collaborators (e.g., Vanderbilt University, a DOE-EERE funded program in solid-state lighting, and National Institute of Standards and Technology [NIST] Gaithersburg), we propose to target advancements in three specific materials systems: (1) realization of truly environment-robust semiconductor nanomaterial photophysics; (2) development of novel dual quantum-emitter structural motifs, "quantum hearts," and core/active-shells; and (3) quantum disks-in-wires. The former two will be pursued synthetically using the auto-reactor combi-chem approach, while the latter takes advantage of a microfluidics-enabled SLS growth process. All, however, will involve directly correlating a target function/behavior with a nanomaterials structural and/or compositional characteristic.

(1) Environmental robustness and long-term reliability of opto-electronic nanomaterials are needed for next-generation lighting, tunable low-threshold lasers, and photodetectors and sensors. Here, an individual nanomaterial PL (intensity/peak position) will be monitored as a function of temperature, oxygen level, humidity and time, and nanoparticles exhibiting different behaviors will be examined by high-resolution imaging, elemental mapping for atomic composition across interfaces (largely with a Vanderbilt University CINT user) [86], and electron energy loss spectroscopy (EELS) for additional information pertaining to lighter

elements, chemical bonding, and valence/conduction-band electronic properties (with NIST Gaithersburg collaborators). By correlating degradations of function with specific changes in structure and/or composition at the single-particle level we will afford unprecedented understanding of the mechanisms responsible for environment-caused deterioration. Such insight should allow us to synthetically engineer a solution to long-standing challenges to nanoparticle performance reliability.

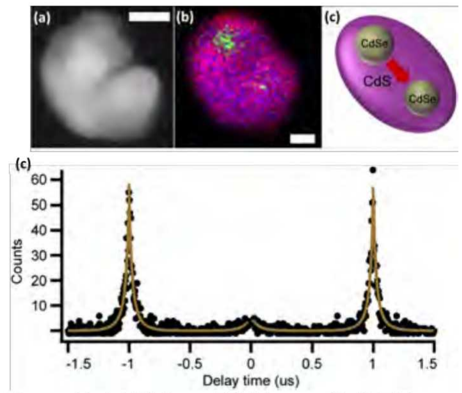

Figure 11. (a) High-res TEM image, (b) STEM-EDS map, and (c) schematic of a quantum heart with two CdSe cores. The $g^{(2)}$ trace (d) shows clear photon antibunching characteristics to the single quantum emitter.

(2) Correlated single-nanoparticle optical spectroscopy/TEM studies will be used as a guide in the development of new two-emitter nanomaterials (see Figure 11). Recently, we discovered in the synthetic product of some core/thick-shell g-QD preparations a heart-shaped particle ("quantum heart") that contains two CdSe cores but behaves as a single quantum emitter, possibly indicating that the two cores are coupled quantum mechanically. Truly coupled QD "molecules" could serve as coupled optical qubits for the realization of various quantum information technologies. A synthetic challenge is to determine which variables of the g-QD synthesis are responsible for dimer formation during shell growth. Automated synthesis will help us to more rapidly assess suspected variables (core identity, anion precursor choice, ligand balance). Single-dot correlated structure/composition-function information will provide insight into specific aspects of the particle's internal structure that might lead to desired quantum mechanical interactions, e.g., entanglements.

(3) Lastly, beyond QD quantum emitters, we will pursue all-solution-processed 2D disk-in-1D wire emitters. Compared with 0D QDs, 2D disk emitters have advantages as single-photon sources—rapid and narrowband emission for improved photon indistinguishability. Embedding such disk-like structures within a wire would afford control over the disk's immediate environment and a possible means for electrically addressing the disk. While quantum disks with 2D electronic properties can now be synthesized using colloidal chemistry and show key properties of 2D electronic structure (fast, narrowband emission), disk-in-wire structures have traditionally been fabricated using metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) techniques. We will use flow-SLS to access novel colloidal quantum disks-in-wires. The low reaction temperatures and ligand-mediated growth are predicted to afford ultra-abrupt disk-wire interfaces, control over disk thickness, and facile access to a wide range of compositions (including II-VI, III-V, IV-VI, I-III-VI compound semiconductors).

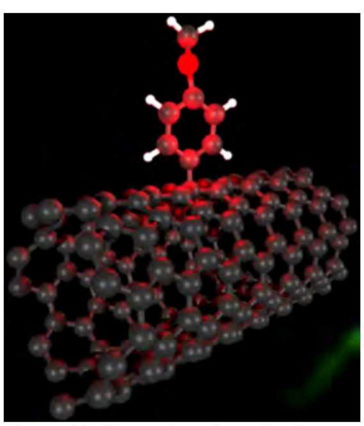

Figure 12. Illustration of covalently bound aryl-diazonium dopant introducing an isolated sp^3 defect in the carbon nanotube structure.

Surface Chemistry, Functionalization, and Synthesis of Carbon Nanomaterials (Doorn)

Low-level covalent functionalization of carbon nanotubes to introduce sp^3 defects (Figure 12) is reinvigorating the area of nanotube photonics by dramatically improving photoluminescence quantum yields (through exciton trapping at these new defect sites) and introducing new functionality (such as truly correlated receptor/transduction sites for sensing, photon upconversion [87], and room-temperature single-photon emission [29]). We will continue to develop functionalization strategies that directly pair dopant sites with desired functionality (such as receptors or redox behavior towards energy-harvesting applications). Strategies for increasing trap defect-site depth (through a user project with the University of MD, U2015A0059) will be implemented as a route for pushing trap-site emission to telecom wavelengths and increasing the thermal stability of this emission behavior. Synthetic routes to local pairing of coupled dopant sites will also be pursued. Improved matrices are also required for doped tube device integration, as there is a need to move from the polar environment of our solid-state doping approach [35] as a means to further stabilize properties for single-photon emission [30]. New matrices will also enable a wider range of deposition strategies for integration into other photonic device and cavity structures as an enabling route to additional user projects (Kyoto University, U2015B0044, and ENS-Cachan in Paris, U2015B0064). Through collaborative efforts and user projects (with Duke University U2013B0126, and NREL, C2015B0129), we are initiating the development of novel polymer wrappings compatible with solution-phase doping as a route to incorporate the doped tubes into reduced-polarity polymer matrices. These systems will also directly enable studies aimed at the elucidation of suggested phonon couplings and extending energy-harvesting functionality. Efforts will also continue to integrate CINT graphene synthesis capability with strategies to create hybrid materials. Examples will include efforts toward large-area single domain growth of twisted bilayer materials in which the resulting optical resonances will be tuned to overlap with anticipated induced plasmons arising from integration with g-QDs [12]. We will also advance our large-area graphene synthesis approaches to include single domain methods that will enable generation of twisted bilayers with defined twist angles. These should have interesting resonance behaviors to look for in coupled QD heterostructures. We will continue to work towards graphene integration with nanowire energy storage materials and complex oxides as well.

6.3.2 Optical Spectroscopy of Low-Dimensional Nanostructures

<u>Development of Novel Spectroscopic Capabilities (Htoon, Doorn, Prasankumar, Efimov)</u>

We are currently acquiring a 9 tesla superconducting magnet and a microscopy cryostat to build a new system capable of performing advanced single-nanostructure spectroscopies (Raman, PL, time-resolved PL, photon correlation spectroscopy, etc.) under a strong magnetic field. A separate microscopy cryostat will allow us to control the temperature of the nanostructures from 4 to 400 K. Combined with existing state-of-the-art lasers and electronic and photon detectors, including the four-channel superconducting nanowire single-photon detector (SNSPD) system, this facility will become a unique capability for exploring electronic fine structure and quantum optical properties of the spin states of a variety of nano materials. Notably, development of this facility will proceed in parallel with extension of our continuously tunable Raman excitation sources further into the UV (to ~270 nm) via a wavelength–doubled dye system. The capability will expand the range of materials on which CINT can perform resonance Raman experiments (with initial targets being exploration of phonon coupling in hybrid multiferroic materials) and will provide an extensive range of excitation (from near-IR to UV) for the magneto microscopy capability. In the area of nanostructure PL imaging, we are extending our correlated two-color techniques to include capability for back focal plane imaging [88], which will provide a new tool for probing the control of emission polarization and directionality and for approaching strong coupling regimes in many of our hybrid emitter/photonic structured materials. The SECARS microscope noted above will be further developed towards meeting the challenging goal of obtaining good signal-to-noise from a biological monolayer, such as lipid membranes within a reasonable acquisition time and at frequencies other than the standard C-H stretching vibration. Advancing our system should allow attempting functional imaging of biosamples. Finally, we are adapting our femtosecond time-resolved SHG system for THz/mid-infrared pumping, which will enable us to photoexcite low-energy excitations and specifically probe the resulting surface/interfacial response in a variety of materials.

<u>Fundamental Photophysics of Low-D Optical Materials (Doorn, Htoon, Prasankumar, Efimov)</u>

We will expand into a new area related to integrated photonics devices based on “spreadable” nonlinear optical (NLO) materials. Through optimization of chemistry, we expect to further increase the NLO response of incorporated thin-film chromophores to become suitable for photonic device design and testing. Inkjet or 3D printing may become possible with these materials. Raman studies of carbon nanotubes will focus on non-Condon behaviors of unexplored phonon modes and using Raman to explore a recent CINT discovery of novel electronic coupling in loosely assembled nanotube aggregates. Continuing the theme of exploring emergent behaviors in coupled systems, beyond the correlated measurements noted above on QD quantum hearts for feedback into synthesis strategies, the synthesis effort will be closely paired with correlated single “heart” optical studies for exploring their quantum optical properties (Figure 11) including photon entanglement. Such quantum optical properties are also a primary interest of ours for the covalently doped carbon nanotubes. Continuing our close interactions with CINT theory capability, we will also probe optical behaviors of coupled covalent dopant pairs in CNTs and evaluate their potential for generating entangled photons as well.

Furthermore, an important aspect of obtaining the narrow emission lines essential for generating indistinguishable single photons for our quantum optics efforts is to devise a route to extend dephasing times for the dopant states. One strategy may be to use polymer systems that effectively act as phonon cutoffs that limit phonon coupling. The role of exciton-phonon coupling in enhancing dopant excitation and emission and also its role in newly revealed photon upconversion will also be explored. Linked to all of these studies will be the first-ever probes of the dynamics of the dopant optical processes, uniquely enabled by our SNSPD capability. These fundamental studies on our quantum emitters will feed directly into efforts aimed at developing low-dimensional defect materials for Quantum Information Technologies. Finally, we will continue our efforts in using ultrafast optical microscopy to temporally and spatially resolve carrier dynamics and transport in quasi-1D semiconductor NWs. These studies have recently been extended to NW heterostructures (e.g., in Si, Ge, and III-nitrides), enabling us to track photoexcited carriers as they relax across multiple dimensions in space and time, potentially impacting applications including light emission and photovoltaics.

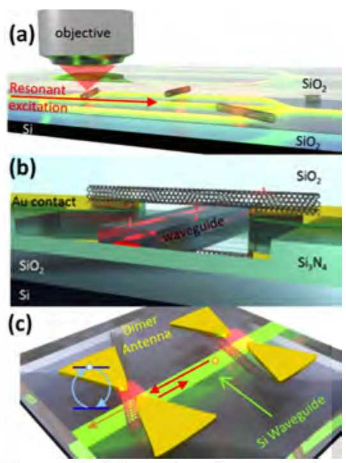

Figure 13. Schematics of prototyped devices. (a) Doped carbon nanotubes coupled to a linear Si waveguide for single-photon generation via resonant light scattering. (b) Electrically driven single-photon sources coupled to a linear waveguide. (c) Doped CNT-based single-photon switch where plasmonic a bow-tie antenna was used to achieve strong-plasmon exciton coupling.

<u>Defect States in 1D and 2D Systems as Building Blocks for Quantum Information Technologies (Htoon, Doorn)</u>

Our discovery of single-photon generation from solitary dopant states of nanotubes [29] will be extended to investigate the potential of defect/dopant states in 2D and 1D nanostructures as new fundamental building blocks for quantum information technologies. Our doped carbon nanotubes encapsulated in SiO_2 matrices present an exciting opportunity to apply existing microelectronic fabrication techniques in the development of electrically driven single-photon sources and integrated quantum photonic networks. Aiming to establish this system as a transformative material for a wide range of quantum information technologies, we will (1) further investigate the quantum optical properties of these defects states, (2) explore chemical approaches to control their electronic structure, and (3) generate proof-of-principle devices demonstrating electrically driven single-photon generation and single-photon switching. Single nanostructure magneto-optical spectroscopy will play a critical role in accomplishing goals (1) and (2). Proof-of-principle devices envisioned in Figure 13 will be pursued in collaboration with the Quantum Computing Grand Challenge team of Sandia National Laboratories. We have also established a CINT user project with Prof. Ralph Krupke of Karlsruhe Institute of Technology for fabrication of electrically driven single-photon sources (Figure 13b). Beyond CNTs, we will also expand our studies toward defects states in 2D materials such as transitional metal dichalcogenides [89–94] and hexagonal boron nitrides [95] where single-photon emission has recently been reported.

6.3.3 Integrated Quantum Photonic and Optomechanical Circuits (Camacho)

Going forward, over the next three years, we plan to extend these initial results to support a variety of users. For example, a recently accepted proposal (RA2015B0013) has the goal of connecting CINT to Tech Areas I and IV at Sandia National Laboratories using microfabricated quantum transceivers in a quantum network [96]. In this project, CINT will literally become a gateway connecting the national lab to CINT and vice versa. We also have new proposals to do nonlinear quantum switching in Xenon vapor, using CINT (U2015B0039) and visitors from the Australian Research Council interested in making CINT a key partner in a new multi-million-dollar quantum optomechanics program.

6.3.4 Emergent Functionality of Mesoscopic Assemblies. (Htoon, Doorn, Brener, Hollingsworth, Efimov)

Integration of our emitters with dielectric meta-material and photonic crystal structures will be pursued as an alternative means for manipulation of fundamental and quantum optical processes of g-QDs and the defect/dopant states of 1D and 2D systems. Through a CINT Core-Gateway collaborative effort, we have already achieved successful coupling of g-QDs and oxygen-doped CNTs to Si dielectric meta-material cavities (Figure 14). Results on doped carbon nanotubes have revealed that the cavity can reorient the linearly polarized dipole of the CNT dopant states. Studies on g-QD silicon pillar cavity coupled systems have also demonstrated the light collimation properties of Si pillars, predicted theoretically. Through a new CINT user project (Prof. Kato, University of Tokyo, U2015A0059), we will fabricate doped CNT-photonic crystal coupled structures and investigate their quantum optical properties. We also plan to integrate these coupled structures into prototype devices to achieve enhanced efficiency and polarization characteristics of single-photon emission in the case of electrically driven single-photon sources (Figure 13b) and to achieve the strong coupling necessary for photon switching in the case of the single switch of Figure 13c. In addition to these single quantum emitter–photonic coupled structures, we will also study metal nanoparticle-g-QD superlattice arrays fabricated through bio-inspired self-assembly approaches for manifestation of collective phenomena such as plasmon assisted lasing and super-radiance.

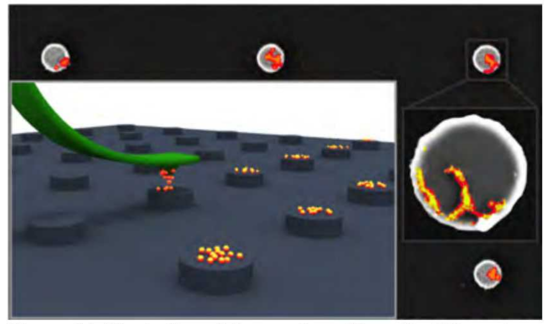

Figure 14. Illustration of dip-pen deposition of g-QDs on to individual Si dielectric pillars. SEM images show actual deposition of InPcore/CdSe:CdS shell g-QDs. Deposition is developed for a range of particle sizes from 10 nm to 50 nm.

In addition to pursuing emergent graphene plasmonic behaviors in twisted bilayer interactions with g-QDs, graphene plasmonics work will also encompass the study of (1) graphene hetero-nanostructures—plasmons and their interaction with substrate phonons to yield dispersion of the hybridized mode, which may find applications in superresolution imaging on a surface; (2) methods to more efficiently excite plasmons and hybrid modes using, e.g., Cherenkov or superluminal mechanisms; (3) interaction of graphene plasmons with nanoparticles, including biological, integrated into the device; (4) full understanding of the hysteretic behavior of the devices, gate voltage control of nanoparticle localization, trapping, and sorting; (5) integration of the graphene plasmonic devices into microfluidic systems and integration with IR metamaterials to create tunable functionalities through graphene backgate voltage control.

6.3.5 Hybrid Metamaterials and Metasurfaces for Advanced Functionality and Optical Nonlinearities (Chen, Brener, Luk)

There is much recent progress in creating and understanding metasurface structures for manipulating light propagation, polarization conversion, wavefront engineering, and beam forming. While we will continue this important direction through designing novel metasurface structures for integrated photonics (U2014B0018), the planar metasurface structures facilitate the integration of functional materials for active control and novel device architecture for improved performance, and the cavity resonances also enable enhanced light-matter interactions, which tremendously magnify the functionality from the integrated materials. We will investigate the photoluminescence, photovoltaics, and photoconductivity of thin-film quantum dots and semiconductors, and 2D van der Waals materials, including graphene, transition metal dichalcogenides, and black phosphorus, when they are integrated within metasurface absorbers. Switchable and frequency-tunable metasurfaces represent an utmost important research direction. We will focus on new switching approaches, device architectures, and functionality, such as graphene metasurface spatial light modulators of interest for multiplexed operation for imaging and communications. We will also extend our success in metasurface antireflection towards the investigation of nonlinear processes of high-refractive-index materials such as strontium titanate at low temperatures, without which it would be otherwise technically challenging to efficiently couple THz radiation into these ferroelectric materials (U2015A0057).

In the area of all-dielectric metasurfaces, recent third-harmonic-generation experiments have shown very high efficiencies when magnetic or electric dipole modes were excited. Creating these metasurfaces (or ultimately, 3D metamaterials) from different materials that possess high intrinsic second-order nonlinearities would allow for new directions in nonlinear optics and a combined generation-manipulation structure for harmonic generation. We have recently established a process to fabricate metasurfaces from AlGaAs-based semiconductors, and preliminary results show record high efficiencies for second-harmonic generation. We will explore other high-index semiconductors and nanofabrication strategies that will allow creation of 2D and 3D dielectric metamaterials at even shorter wavelengths. Further integration of such all-dielectric metamaterials with light-emitting nanostructures (i.e., quantum dots or quantum wells) would allow for exquisite control of the radiative rates in combination with far-field beam-shaping possibilities. The integration of 1D and 2D materials (CNTs, transition metal dichalccogenides [TMDCs], etc.) with these all-dielectric metasurfaces will also be explored. In the area of light harvesting, we will explore the use of ENZ modes based on available enhancements that create strong oscillating fields at materials interfaces. This can induce DC currents through a rectification process in homo- or hetero-pn junctions. Experimental demonstration of this phenomenon in a metal-oxide-semiconductor structure using longitudinal optical phonons as the ENZ material was recently published [97]. We plan to use plasmonic ENZ materials (such as In_2O_3, CdO, and doped InAs) and two-layer pn junction structures to produce this rectification effect. By using hyperbolic metamaterials, both ENZ frequency and mode dispersion can be tuned readily and can dramatically enhance performance through better coupling and broader spectral response [98].

Several new paths for creating very high Q resonances from all-dielectric metasurfaces have recently been unveiled by us and other groups [99–101]. We plan on investigating transient phenomena of these new metasurfaces when optically pumped below and above the bandgap of the constituents. We anticipate interesting venues for optical switching since these high Q resonances can be affected by two-photon absorption, creation of electron-hole pairs, and/or transient bandgap renormalization. Devising very high Q resonances for metasurfaces also offers interesting possibilities for chem-bio sensing, and these will be explored in collaboration with our user community.

6.3.6 Ultrafast Spectroscopic Studies (Prasankumar)

Ultrafast Optical and THz Spectroscopy of Dirac and Weyl Semimetals

Dirac and Weyl semimetals (DSM and WSM, respectively) have gained recent attention, as they exhibit the linear energy dispersion of graphene in a 3D material, leading to a host of novel properties (e.g., the chiral anomaly, large magnetoresistance, and Fermi arcs). Both static and time-resolved optical spectroscopy should shed light on the physics of WSM/DSM, particularly since theoretical predictions have shown that optical conductivity measurements can verify the existence of the WSM/DSM state [102]. Therefore, we have recently begun using optical spectroscopy to explore Dirac physics in these systems, in collaboration with CINT users at the Chinese Academy of Sciences. Initial measurements on the WSM TaAs using FTIR spectroscopy have revealed optical signatures of Weyl points lying in close proximity to the Fermi energy (Figure 15) [103]. We will build upon these initial results by exploring carrier relaxation in TaAs and the DSM Cd_3As_2 using temperature-dependent all-optical pump-probe spectroscopy. Using a THz magneto-optical spectroscopy system developed at CINT, we will then explore cyclotron resonance and the quantum Hall effect in these systems; it is worth noting that Kerr/Faraday rotation measurements may shed light on the chiral anomaly, a novel effect specific to WSM that was theoretically predicted but has not yet been experimentally observed. Finally, optical-pump, THz-probe (OPTP) experiments, particularly under a DC magnetic field, should provide more insight into carrier dynamics in these materials.

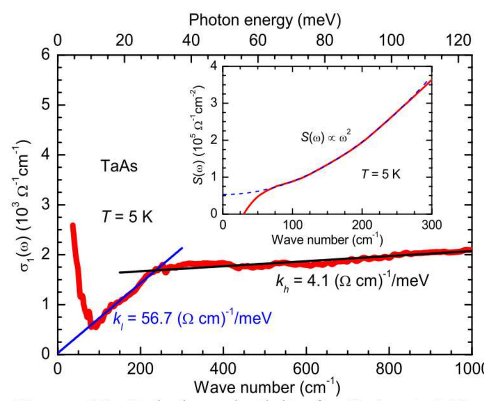

Figure 15. Optical conductivity for TaAs at 5 K. The blue and black solid lines through the data are guides to the eye. The inset shows the spectral weight vs. frequency at 5 K.

Driving Low-Energy Excitations in Natural and Artificial Magnetoelectric Multiferroics

Low-energy excitations (e.g., phonons and magnons) occurring at mid-to-far–IR frequencies are fundamentally linked to the complex order parameters that exist in strongly correlated electron materials. One can thus gain substantial insight into the properties of these materials by studying these modes, particularly their evolution in time. This has been very useful in studying ME multiferroic materials in which magnetic and FE order parameters coexist and are often coupled (Section 6.2.2). By directly driving these low-energy excitations [104], researchers can unravel their coupling to other degrees of freedom and potentially control ME coupling in multiferroics at unprecedented timescales. At CINT, we have recently generated intense far-IR pulses with electric fields of ~100 kV/cm at ~1.7 THz. We have used this to drive nonlinear transport in the FM manganite $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) (Figure 16); this can be extended to the oxide heterostructures discussed above in Section 6.2.2, enabling us to explore how driving a FM layer with intense THz pulses would influence FE order in an adjacent layer. We have also used THz pulses to directly probe magnon dynamics in the bulk multiferroic $HoMnO_3$, revealing that energy is transferred from photoexcited electrons to magnons through the lattice degree of freedom [105]. Here too, driving the magnon mode with an intense THz pulse could enable us to unravel the coupling between magnetic and FE order in this material. More insight could be obtained by performing both OPTP and THz-pump, optical/THz-probe experiments under a DC magnetic field on both bulk multiferroics and multiferroic heterostructures. Finally, we can also drive FE order by photoexciting soft-mode phonons; doing this in FE/FM heterostructures could again enable us to dynamically control ME coupling in these heterostructures, with direct relevance towards potential applications in, e.g., data storage. More generally, the ability to drive low-energy excitations with intense IR pulses should attract new users from a variety of fields, ranging from biology to solar energy to condensed-matter physics.

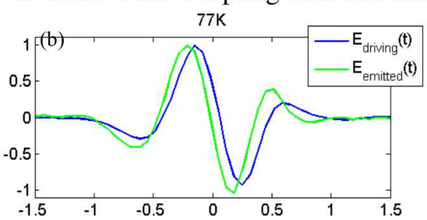

Figure 16. Driving (blue) and emitted (green) THz fields transmitted through the manganite LCMO.

7.0 Publications

7.1 Literature Cited

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7.2. Publications from Previous Support

	NPON Publication Count			
NSRC High Impact Journals	**2013**	**2014**	**2015**	**Total**
ACS Nano	2	4	5	**11**
Advanced Functional Materials	0	2	2	**4**
Advanced Materials	0	0	0	**0**
Angewandte Chemie International Edition	0	0	0	**0**
Applied Physics Letters	12	11	10	**33**
Chemistry of Materials	0	0	0	**0**
Journal of the American Chemical Society	0	0	1	**1**
Nano Letters	3	5	6	**14**
Nanoscale	1	1	5	**7**
Nature	0	0	0	**0**
Nature Chemistry	0	0	0	**0**
Nature Communications	1	2	1	**4**
Nature Materials	0	0	0	**0**
Nature Nanotechnology	2	0	1	**3**
Nature Photonics	2	0	0	**2**
Nature Physics	0	0	0	**0**
Physical Review Letters	2	0	1	**3**
Proceedings of the National Academy of Sciences USA	0	0	0	**0**
Science	1	0	0	**1**
Small	0	2	1	**3**
TOTAL:	26	27	33	**86**

NPON

2013 Publication total: 68
CINT science: 19
CINT user science (internal): 26
CINT user science (external):23

2014 Publication total: 60
CINT science: 11
CINT user science (internal):17
CINT user science (external):32

2015 Publication total: 89
CINT science: 13
CINT user science (internal): 28
CINT user science (external):48

Note: CINT Scientist authors are indicated in red; CINT User authors are indicated in green (external) and orange (internal).

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8.0 Biographical Sketches

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Los Alamos National Laboratory, Director's Postdoctoral Fellow (1990-1992)

Selected Publications

Ma, X.; Hartmann, N.F.; Baldwin, J.K.S.; Doorn, S.K.; Htoon, H.; "Room Temperature Single Photon Generation from Solitary Dopants in Single Wall Carbon Nanotubes", *Nature Nanotech*., **10**, 671 (2015).

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Awards and Synergistic Activities

Honors:

LANL Distinguished Performance Award, 1998.
Defense Programs Award of Excellence, 2001, 2003.
Nanotech Briefs Nano50 Award for development of ultralong carbon nanotubes, 2005.
DOE Office of Science Outstanding Mentor Award, 2008.
LANL Fellows Prize for Research, 2011.
Fellow of the American Physical Society, 2014.

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Professional Experience
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Center for Integrated Nanotechnologies, Nanophotonics Thrust Leader (2008-2015)
Sandia National Laboratories, Principal Member of the Technical Staff (2004-2013)
Amersham Biosciences/GE Healthcare, Senior Scientist (2003-2004)
Tellium Inc., Senior Member of Technical Staff (2000-2002)
Bell Laboratories, Lucent Technologies & AT&T, Member of Technical Staff, (1993–2000)
Bell Laboratories, Postdoctoral Member of Technical Staff (1991-1993)
National Semiconductor, Senior Electronic Engineer in VLSI MOS and Head of NS32332 microprocessor testing group (1983-1987)

Publications

1. *“Polarization-Independent Silicon Metadevices for Efficient Optical Wavefront Control”*, Katie E. Chong, Isabelle Staude, Anthony James, Jason Dominguez, Sheng Liu, Salvatore Campione, Ganapathi S. Subramania, Ting S. Luk, Manuel Decker, Dragomir N. Neshev, Igal Brener, and Yuri S. Kivshar, *Nano Letters* 2015 *15* (8), 5369-5374, DOI: 10.1021/acs.nanolett.5b01752
2. *“Photoconductive Terahertz Near-Field Detector with a Hybrid Nanoantenna Array Cavity”,* Oleg Mitrofanov, Igal Brener, Ting Shan Luk, and John L. Reno, ACS Photonics 2, 1763 (2015).
3. *“Phased-array sources based on nonlinear metamaterial nanocavities”,* Omri Wolf, Salvatore Campione, Alexander Benz, Arvind P. Ravikumar, Sheng Liu, Ting S. Luk, Emil A. Kadlec,Eric A. Shaner, John F. Klem, Michael B. Sinclair & Igal Brener, Nature Communications 6, Article number: 7667 (2015)
4. *Continuous and dynamic spectral tuning of single nanowire lasers with subnanometer resolution using hydrostatic pressure”*, S Liu, C Li, JJ Figiel, SRJ Brueck, I Brener, GT Wang, Nanoscale 7 (21), 9581-9588 (2015)
5. *“Control of Strong Light–Matter Coupling Using the Capacitance of Metamaterial Nanocavities”*, Alexander Benz, Salvatore Campione, John F. Klem, Michael B. Sinclair, and Igal Brener, *Nano Letters* Article ASAP, DOI: 10.1021/nl504815c
6. *“Enhanced Third-Harmonic Generation in Silicon Nanoparticles Driven by Magnetic Response”*, Maxim R. Shcherbakov, Dragomir N. Neshev, Ben Hopkins, Alexander S. Shorokhov, Isabelle Staude, Elizaveta V. Melik-Gaykazyan, Manuel Decker, Alexander A. Ezhov, Andrey E. Miroshnichenko, Igal Brener, Andrey A. Fedyanin, and Yuri S. Kivshar, Nano Letters *14,* 6488-6492 (2014).
7. *“Optical magnetic mirrors without metals”*, Sheng Liu, Michael B. Sinclair, Thomas S. Mahony, Young Chul Jun, Salvatore Campione, James Ginn, Daniel A. Bender, Joel R. Wendt, Jon F. Ihlefeld, Paul G. Clem, Jeremy B. Wright, and Igal Brener, Optica 1, 250-256 (2014).
8. *“Spectrally selective chiral silicon metasurfaces based on infrared Fano resonances”*,

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9. "Realizing Optical Magnetism from Dielectric Metamaterials", J.C. Ginn, I. Brener, D.W. Peters, J.R. Wendt, J.O. Stevens, P.F. Hines, L.I. Basilio, L.K. Warne, J.F. Ihlefeld, P.G. Clem, M.B. Sinclair, Phys. Rev. Lett. 108, 97402 (2012)
10. "Strong Coupling between Nanoscale Metamaterials and Phonons", D.J. Shelton, I. Brener, J. C. Ginn, M. B. Sinclair, D. W. Peters, K. R. Coffey, and G. D. Boreman, Nano Lett. 11, 2104 (2011)

Awards and Synergistic Activities

<u>Honors:</u>

- Fellow of the IEEE (2013)
- Lady Davis Fellow (2012)
- Award for Research Excellence, SNL, Grand Challenge Metamaterials (2011)
- LDRD Award for Excellence, SNL, Miniature Flow Cytometer (2008)
- Fellow of the Optical Society of America (2007)
- Award of Excellence, Bell Labs (1999)
- Rotschild scholarship for post-doctoral studies (1991-1993)
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- Sudents: Pete Sinclair, undergrad, Washington State, 2015, Jeremy Wright, Ph.D., UNM, 2014, J. Briscoe, NMSU, PhD, 2014, J. Sanchez, La Cueva HS, 2014, Tim Lopez, undergrad UNM, Tom Mahony, Physics UNM

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Education

B. S. in Physics	Brigham Young University, Provo, UT, 2003
M.A.. in Physics	University of Rochester, Rochester, NY, 2005
Ph.D.. in Physics	University of Rochester, Rochester, NY, 2008

Professional Experience

Center for Integrated Nanotechnologies, Staff Scientist (2013-present)
Sandia National Laboratories, Senior Member of the Technical Staff (2010-present)
California Institute of Technology, Postdoctoral Scholar (2008-2010)
Applied Materials, Student Intern, 2000-2003

Publications

Daniel BS Soh et al., Self-referenced continuous-variable quantum key distribution protocol , *Phys. Rev. X,* **5**, 041010 (2015)

SM Hendrickson et al., Integrated nonlinear photonics: emerging applications and ongoing challenges [Invited], *JOSA B*, **31**, 3193 (2014)

Hendrickson, S. M. *et al*. All-optical-switching demonstration using two-photon absorption and the Zeno effect. *Phys. Rev.A* **87,** 023808 (2013).

Clader, B. D., Hendrickson, S. M., Camacho, R. M. & Jacobs, B. C. All-optical microdisk switch using EIT. *Opt. Express* **21,** 6169–6179 (2013).

Rakich, P. T., Reinke, C., Camacho, R., Davids, P. & Wang, Z. Giant Enhancement of Stimulated Brillouin Scattering in the Subwavelength Limit. *Phys. Rev. X* **2,** 011008 (2012).

Camacho, R. M. Entangled photon generation using four-wave mixing in azimuthally symmetric microresonators. *Opt. Express* **20,** 21977–21991 (2012).

Vudyasetu, P. K., Camacho, R. M. & Howell, J. C. Rapidly reconfigurable slow-light system based on off-resonant Raman absorption. *Phys. Rev.A* **82,** 053807 (2010).

Lin, Q. *et al*. Coherent mixing of mechanical excitations in nano-optomechanical structures. *Nat Photon* **4,** 236–242 (2010).

Eichenfield, M., Chan, J., Camacho, R. M., Vahala, K. J. & Painter, O. Optomechanical crystals. *Nature* **462,** 78–82 (2009).

Eichenfield, M., Camacho, R., Chan, J., Vahala, K. J. & Painter, O. A picogram- and nanometre-scale photonic-crystal optomechanical cavity. *Nature* **459,** 550–555 (2009).

Chan, J., Eichenfield, M., Camacho, R. & Painter, O. Optical and mechanical design of a "zipper" photonic crystaloptomechanical cavity. *Opt. Express* **17,** 3802–3817 (2009).

Camacho, R. M., Vudyasetu, P. K. & Howell, J. C. Four-wave-mixing stopped light in hot atomic rubidium vapour. *Nat Photon* **3,** 103–106 (2009).

Camacho, R. M., Dixon, P. B., Glasser, R. T., Jordan, A. N. & Howell, J. C. Realization of an All-Optical Zero to π Cross-Phase Modulation Jump. *Phys. Rev. Lett.* **102,** 013902 (2009).

Camacho, R. M., Chan, J., Eichenfield, M. & Painter, O. Characterization of radiation pressure and thermal effects in a nanoscale optomechanical cavity. *Opt. Express* **17,** 15726–15735 (2009).

Vudyasetu, P. K., Camacho, R. M. & Howell, J. C. Storage and Retrieval of Multimode

Transverse Images in Hot Atomic Rubidium Vapor. *Phys. Rev. Lett.* **100,** 123903 (2008).
Broadbent, C. J., Camacho, R. M., Xin, R. & Howell, J. C. Preservation of Energy-Time Entanglement in a Slow Light Medium. *Phys. Rev. Lett.* **100,** 133602 (2008).
Shi, Z., Boyd, R. W., Camacho, R. M., Vudyasetu, P. K. & Howell, J. C. Slow-Light Fourier Transform Interferometer. *Phys. Rev. Lett.* **99,** 240801 (2007).
Pack, M. V., Camacho, R. M. & Howell, J. C. Transients of the electromagnetically-induced-transparency-enhanced refractive Kerr nonlinearity. *Phys. Rev.A* **76,** 033835 (2007).
Pack, M. V., Camacho, R. M. & Howell, J. C. Electromagnetically induced transparency line shapes for large probe fields and optically thick media. *Phys. Rev.A* **76,** 013801 (2007).
Camacho, R. M., Pack, M. V., Howell, J. C., Schweinsberg, A. & Boyd, R. W. Wide-Bandwidth, Tunable, Multiple-Pulse-Width Optical Delays Using Slow Light in Cesium Vapor. *Phys. Rev. Lett.* **98,** 153601 (2007).
Camacho, R. M., Broadbent, C. J., Ali-Khan, I. & Howell, J. C. All-Optical Delay of Images using Slow Light. *Phys. Rev. Lett.* **98,** 043902 (2007).
Pack, M. V., Camacho, R. M. & Howell, J. C. Transients of the electromagnetically-induced-transparency-enhanced refractive Kerr nonlinearity: Theory. *Phys. Rev.A* **74,** 013812 (2006).
Camacho, R. M., Pack, M. V. & Howell, J. C. Slow light with large fractional delays by spectral hole-burning in rubidium vapor. *Phys. Rev.* **74,** 033801 (2006).
Camacho, R. M., Pack, M. V. & Howell, J. C. Low-distortion slow light using two absorption resonances. *Phys. Rev.A* **73,** 063812 (2006).

Awards and Synergistic Activities:

Collaborators: G. Subramania, D. Branch, E. Shaner, M. Eichenfield, P. Davids, A. Fischer, J. Urayama, T. Lentine, J. Cox, M. Grace, D. Soh, M. Sarovar, *Sandia National Laboratories, Albuquerque, NM*; Prem Kumar, Salim Shariar, *Northwestern University*; Scott Hendrickson, Chad Weiler, *Applied Physics Lab;* Jim Franson, Todd Pittman, *UMBC;* John Howell, Robert Boyd, *University of Rochester*; Norbert Lutkenhaus, *University of Waterloo*

Graduate and Postdoctoral Advisors: *John Howell, Physics Dept, University of Rochester, NY; Robert Boyd, Optics Dept., University of Rochester, NY, Oskar Painter, Caltech, Pasadena, CA.*

Thesis Advisor and Postgraduate-Scholar Sponsor: (over the last 5 years)

Students: Name, Drew Brost, Washington University in St. Louis, Lillian Acosta, UNM, Mottaleb Hossain, UNM

Postdocs: Ian Frank, Harvard University, Jeremy Moore, University of Michigan, Matt Tomes, University of Michigan, Francisco Benito, UNM,

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Education

Ph.D.	2004	Physics	Rensselaer Polytechnic Institute
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B.S.	1997	Physics	University of Science and Technology of China

Professional Experience

06/2008 – Present Technical Staff Member Los Alamos National Laboratory
05/2005 – 05/2008 Postdoctoral Research Associate Los Alamos National Laboratory

Selected Publications

L. Liang, M. Qi, J. Yang, X. Shen, J. Zhai, W. Xu, B. Jin, W. Liu, Y. Feng, C. Zhang, H. Lu, H.-T. Chen, L. Kang, W. Xu, J. Chen, T. J. Cui, P. Wu, and S. Liu, "Anomalous terahertz reflection and scattering by flexible and conformal coding metamaterials," Adv. Opt. Mater. 3, 1374 (2015).

J. Li, S. Chen, H. Yang, J. Li, P. Yu, H. Cheng, C. Gu, H.-T. Chen, and J. Tian, "Simultaneous control of light polarization and phase distributions using plasmonic metasurfaces," Adv. Funct. Mater. 25, 704 (2015).

B. Zhang, J. Hendrickson, N. N. Esfahani, H.-T. Chen, and J. Guo, "Metasurface optical antireflection coating," Appl. Phys. Lett. 105, 241113 (2014).

J. E. Heyes, W.Withayachumnankul, N. K. Grady, D. Roy Chowdhury, A. K. Azad, and H.-T. Chen, "Hybrid metasurface for ultra-broadband terahertz modulation," Appl. Phys. Lett. 105, 181108 (2014).

N. Karl, K. Reichel, H.-T. Chen, A. J. Taylor, I. Brener, A. Benz, J. L. Reno, R. Mendis, and D. M. Mittleman, "An electrically driven terahertz metamaterial diffractive modulator with more than 20 dB of dynamic range," Appl. Phys. Lett. 104, 091115 (2014).

N. K. Grady, J. E. Heyes, D. Roy Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. R. Dalvit, and H.-T. Chen, "Terahertz metamaterials for linear polarization conversion and anomalous refraction," Science 340, 1304 (2013).

S. Zhang, J. F. Zhou, Y.-S. Park, J. Rho, R. Singh, S. Nam, A. K. Azad, H.-T. Chen, X. B. Yin, A. J. Taylor, and X. Zhang, "Photoinduced handedness switching in terahertz chiral metamolecules," Nat. Commun. 3, 942 (2012).

J. Q. Gu, R. Singh, X. J. Liu, X. Q. Zhang, Y. F. Ma, S. Zhang, S. A. Maier, Z. Tian, A. K. Azad, H.-T. Chen, A. J. Taylor, J. G. Han, and W. L. Zhang, "Active control of electromagnetically induced transparency analogue in terahertz metamaterials," Nat. Commun. 3, 1151 (2012).

H.-T. Chen, "Interference theory of metamaterial perfect absorbers," Opt. Express 20, 7165 (2012).

R. Singh, A. K. Azad, Q. X. Jia, A. J. Taylor, and H.-T. Chen, "Thermal tunability in terahertz metamaterials fabricated on strontium titanate single-crystal substrates," Opt. Lett. 36, 1230 (2011).

H.-T. Chen, H. Yang, R. Singh, J. F. O'Hara, A. K. Azad, S. A. Trugman, Q. X. Jia, and A. J. Taylor, "Tuning the resonance in high temperature superconducting terahertz metamaterials," Phys. Rev. Lett. 105, 247402 (2010).

H.-T. Chen, J. F. Zhou, J. F. O'Hara, F. Chen, A. K. Azad, and A. J. Taylor, "Antireflection

coating using metamaterials and identification of its mechanism," Phys. Rev. Lett. 105, 073901 (2010).
H.-T. Chen, W. J. Padilla, M. J. Cich, A. K. Azad, R. D. Averitt, and A. J. Taylor, "A metamaterial solid-state terahertz phase modulator," Nat. Photon. 3, 148 (2009).
H.-T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, and W. J. Padilla, "Experimental demonstration of frequency agile terahertz metamaterials," Nat. Photon. 2, 295 (2008).
H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," Nature 444, 597 (2006).

Awards and Synergistic Activities
Honors:
LANL Fellows' Prize (2016)
APS Fellow (2015)
LANL Achievement Award (2007, 2013)
LANL Postdoctoral Publication Prize Honorable Mention (2007)

Collaborators
B. S. Alexandrov (LANL), A. K. Azad (LANL), I. Brener (SNL), S. Chen (Nankai University, China), T. J. Cui (Southeast University, China), D. A. R. Dalvit (LANL), D. Gracias (Johns Hopkins University), L. Huang (Harbin Institute of Technology, China), Q. X. Jia (LANL), T. S. Luk (SNL), J. S. Martinez (LANL), D. M. Mittleman (Rice University), K. A. Nelson (MIT), J. F. O'Hara (Oklahoma State University), W. J. Padilla (Duke University), M. T. Reiten (LANL), D. R. Smith (Duke University), C. M. Soukoulis (Iowa State University), A. J. Taylor (LANL), J. Tian (Nankai University, China), S. A. Trugman (LANL), W. Withayachumnankul (University of Adelaide, Australia), H. Yang (Nanjing University of Aeronautics and Astronautics, China), D. Yarotski (LANL), S. Zhang (University of Birmingham, UK), W. L. Zhang (Oklahoma State University), X. Zhang (UC Berkeley), J. F. Zhou (South Florida University).

Thesis Advisor and Postdoc Sponsor
R. Kersting (University of Munich), T.-M. Lu (Rensselaer Polytechnic Institute), R. D. Averitt (UCSD), A. J. Taylor (LANL)

Supervision of Postdocs, Students, and Visiting Scholars
R. Singh (Nanyang Technological University), J. F. Zhou (South Florida University), L. Huang (Harbin Institute of Technology), N. K. Grady (SNL), J. E. Heyes (MIT), S. Silva (South Florida University), Beibei Zeng (LANL), Chun-Chieh Chang (LANL)
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Education

Ph.D. in Physics	University of Florida, Gainesville, 2000
B.S. in Physics	Nizhny Novgorod State University, Russia, 1993

Prodessional Experience

2004-Present	Los Alamos National Laboratory, Technical Staff
2001-2004	Director's funded postdoc, LANL

Selected Publications

D. Prasai, A. R. Klots, AKM Newaz, J. S. Niezgoda, N. J. Orfield, C. A. Escobar, A. Wynn, A. Efimov, G. K. Jennings, S. J. Rosenthal, K. I. Bolotin, "Electrical Control of near-Field Energy Transfer between Quantum Dots and Two-Dimensional Semiconductors," *Nano Letters* **15**, 4374 (2015).

A. Efimov, "Spatial coherence at the output of multimode optical fibers," Optics Express **22**, 15577 (2014).

A. Efimov, "Lateral-sheering, delay-dithering Mach-Zehnder interferometer for spatial coherence measurement," *Optics Letters*, **38**, 4522(2013).

K. A. Velizhanin, A. Efimov, "Probing plasmons in graphene by resonance energy transfer," *Phys. Rev. B* **84**, 085401 (2011)

S. H. Nam, J. Zhou, A. J. Taylor, and A. Efimov, "Dirac dynamics in one-dimensional graphene-like plasmonic crystals: pseudo-spin, chirality, and diffraction anomaly," *Opt. Express* **18**, 25329-25338 (2010).

I. Grigorenko, A. Efimov, "Control of the temporal profile of the local electromagnetic field near metallic nanostructures," *New Journal of Physics* **11,** 105042 (2009) .

A. Efimov, "Fundamental nonlinear-optical interactions in photonic fibers: time-spectral visualization," *Laser Physics*, **18**, 667 (2008).

F. G. Omenetto, N. A. Wolchover, M. R. Wehner, M. Ross, A. Efimov, A. J. Taylor, V. V. R. K. Kumar, A. K. George, J. C. Knight, N. Y. Joly, P. St. J. Russell, "Supercontinuum generation in sub-centimeter lengths of high-nonlinearity photonic crystal fiber," *Optics & Photonics News*, **17**, 35 (2006).

A. Efimov, A. V. Yulin, D. V. Skryabin, J. C. Knight, N. Joly, F. G. Omenetto, A. J. Taylor, P. St. J. Russell, "Interaction of an optical soliton with a dispersive wave," *Phys. Rev. Lett.* **95**, 213902 (2005).

A. Efimov, A. J. Taylor, and F. G. Omenetto, A. V. Yulin, N. Y. Joly, F. Biancalana, D. V. Skryabin, J. C. Knight, and P. St. J. Russell, "Time-spectrally-resolved ultrafast nonlinear dynamics in small-core photonic crystal fibers: Experiment and modeling," *Opt. Express* **12**, 6498 (2004).

W. H. Reeves, D. V. Skryabin, F. Biancalana, J. C. Knight, P. St. J. Russell, F. G. Omenetto, A. Efimov, A. J. Taylor, "Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibers," *Nature* **424**, 511 (2003).

Awards and Synergistic Activities
Honors:

2002	Los Alamos achievement award
2001	Los Alamos director's postdoctoral fellowship
1999	T. A. Scott Memorial fellowship, best experimentalist graduate student

Collaborators
J. Martinez, K. Velizhanin, D. Yarotski, A. Azad, H. T. Chen, A. J. Taylor, A. Bishop, E. Simakov, J. George - Los Alamos National Lab; A. Neumann - U of New Mexico; Y. H. Xie – UCLA; K. Bolotin - Vanderbilt U.; F. Omenetto - Tufts U. R. Driben, U. of Paderborn, Germany; B. Malomed - Tel Aviv U., Israel; A. Yulin - U. of Lisbon, Portugal and ITMO, Saint Petersburg, Russia; G. Gelikonov – Institute of Applied Physics, Russia; D. Skryabin - U. of Bath, UK; E. Vanin - ACREO, Sweden; F. Mertens – U. Bayreuth, Germany; N. Quintero – U. de Sevilla, Spain;

Graduate and Postdoctoral Advisers: David Reitze, University of Florida (currently director of LIGO, CalTech); A. J. Taylor, Los Alamos National Laboratory

Thesis Advisor and Postgraduate - Scholar Sponsor: Postdocs: Z. Chen, S. H. Nam, A. Singh, I. Grigorenko, K. Velizhanin. Students: Z. Yan, A. Wynn Noble. Total: 5 postdocs, 2 students.

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Education

PhD	Dec. 2001	Physics, University of Texas at Austin, Austin, Texas
MS	May 1996	Physics, Western Illinois University, Macomb, Illinois
BS	Dec. 1991	Physics (Honors), University of Yangon, Yangon, Myanmar

Professional Experience

Technical Staff Member, Los Alamos National Lab	Nov. 2005 – present
Director's Postdoctoral Fellow, Los Alamos National Lab	Dec. 2001-Nov. 2005

Selected Publications (out of 77; >4000 citations; H-index 30)

1. Ma, X.; Baldwin, J. K. S.; Hartmann, N. F.; Doorn, S. K.; Htoon, H., Solid-State Approach for Fabrication of Photostable, Oxygen-Doped Carbon Nanotubes. *Adv. Funct. Mater*, *25* (39), 6157 (2015). **(Front Cover)**.
2. Ma, X.; Hartmann, N. F.; Baldwin, J. K. S.; Doorn, S. K.; Htoon, H., Room Temperature Single-Photon Generation from Solitary Dopants of Carbon Nanotubes. *Nat. Nanotechnol.* **10**, 671, (2015).
3. Wang, F.; Karan, N. S.; Nguyen, H. M.; Ghosh, Y.; Sheehan, C. J.; Hollingsworth, J. A.; Htoon, H., Quantum Optical Signature of Plasmonically Coupled Nanocrystal Quantum Dots. *Small 11,* 5028-5034 (2015). **(Back Cover)**
4. Wang, F.; Karan, N. S.; Nguyen, H. M.; Ghosh, Y.; Sheehan, C. J.; Hollingsworth, J. A.; Htoon, H., Correlated Structural-Optical Study of Single Nanocrystals in a Gap-Bar Antenna: Effects of Plasmonics on Excitonic Recombination Pathways. *Nanoscale* **7** (21), 9387-9393, (2015).
5. Ma, X., Adamska, L., Yamaguchi, H., Yalcin, S. E., Tretiak, S., Doorn, S. K. & Htoon, H. Electronic Structure and Chemical Nature of Oxygen Dopant States in Carbon Nanotubes. *Acs Nano* **8**, 10782-10789, (2014).
6. Ma, X., Roslyak, O., Wang, F., Duque, J. G., Piryatinski, A., Doorn, S. K. & Htoon, H. Influence of Exciton Dimensionality on Spectral Diffusion of Single-Walled Carbon Nanotubes. *Acs Nano* **8**, 10613-10620, (2014).
7. Gao, Y., Roslyak, O., Dervishi, E., Karan, N. S., Ghosh, Y., Sheehan, C. J., Wang, F., Gupta, G., Mohite, A., Dattelbaum, A. M., Doorn, S. K., Hollingsworth, J. A., Piryatinski, A. & Htoon, H. Hybrid Graphene–Giant Nanocrystal Quantum Dot Assemblies with Highly Efficient Biexciton Emission. *Advanced Optical Materials* **3**, 39-43, (2015).
8. Mangum, B. D., Wang, F., Dennis, A. M., Gao, Y., Ma, X., Hollingsworth, J. A. & Htoon, H. Competition between Auger Recombination and Hot-Carrier Trapping in PL Intensity Fluctuations of Type II Nanocrystals. *Small* **10**, 2892, (2014).
9. Park, Y.-S., Ghosh, Y., Chen, Y., Piryatinski, A., Xu, P., Mack, N. H., Wang, H.-L., Klimov, V. I., Hollingsworth, J. A. & Htoon, H. Super-Poissonian Statistics of Photon Emission from Single Core/Shell Nanocrystals Coupled to Metal Nanostructures *Phys. Rev. Lett.* **110**, 117401, (2013).
10. Galland, C., Ghosh, Y., Steinbrück, A., Sykora, M., Hollingsworth, J. A., Klimov, V. I. & Htoon, H. Two types of luminescence blinking revealed by spectroelectrochemistry of single quantum dots. *Nature* **479**, 203-207, (2011)

Awards and Synergistic Activities

Awards

Los Alamos Achievement Award (2015)
LANL Associate Directorate for Chemistry, Life, and Earth Sciences Achievement Award for Program Development (2009)
Postdoctoral Distinguish Performance Award, Los Alamos National Laboratory (2005)
Achievement Award, Los Alamos National Laboratory (2003)
Director's Postdoctoral Fellowship, Los Alamos National Laboratory (2001)
Outstanding Poster Award, MRS 1999 Fall Meeting
Best Graduate Student Award (1996), Department of Physics, Western Illinois University

Synergistic Activities

Invited speaker at: MRS(2015); APS (2014, 2005, 2007), SPIE (2013, 2006), ECS (2008), FACSS (2006), and CLEO(2001).
Chair/organizer for: 2014 MRS Spring Meeting, Symposium TT, 2015 MRS Spring Symposium WW, 2016 MRS Spring Symposium NT,
Technical reviewer for: DOE Early Career Research Program (2010-2014); Nat. Photon. Nat. Nanotechnol., Nat. Comm., Sci. Rep., Phys. Rev. Lett., Phys. Rev. B, J. Am. Chem. Soc., Nano Lett., ACS Nano, Adv. Mater., Small, J. Phys. Chem. Lett., Nanoscale, etc.

Collaborators: Los Alamos National Laboratory: V. I. Klimov, S. Crooker, J. A. Hollingsworth, A. Taylor, S. T. Picraux, I. H. Campbell, S. K. Doorn, R. D. Schaller, J. M. Pietryga, M. Sykora ; Rice University: J. Kono, Niaome Halaas; Washington University: R. A. Loomis; Arizona State University: Hongbin Yu; University of New Mexico/University of California (Los Angeles) Diana Huffaker; University of Texas at Dallas: Anton V. Malko, Anvar A. Zakhidov

Graduate and Postdoctoral Advisors: C. K. Shih, University of Texas at Austin; V. I. Klimov, LANL.

Thesis Advisor and Postgraduate-Scholar Sponsor: (over the last 5 years)
Students (Total: 2): McKay Parkison, Univ. Utah, Christina Hanson, LAL.
Postdocs (Total: 15): Yongshin Park, UNM, Sergio Brovelli, Univ. Milano Bicocca; Bhola N. Pal, Indian Inst. Tech.; Christophe Galland, EPFL Lausanne; Sanjeev Singh, Geogia Tech; Benjamin D. Mangum, Pacific Light Tech.; Yongqian Gao, Nanjing Uni. Sci & Tech; Aditya Mohite, LANL, Melissa Paulite; Hue Minh Nguyen; Feng Wang, Emory Univ; Xuedan Ma, Sandia National Lab.; Nicolai F. Hartmann, LANL, Noah J. Orfield, LANL; Zhongjian Hu, LANL; Xiaowei He, LANL.

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Education

B.A. in Chemistry	Grinnell College, Grinnell, IA 1992
Ph.D. in Inorganic Chemistry	Washington University, St. Louis, MO, 1999

Professional Experience

Los Alamos National Laboratory, Materials Physics & Applications Division, Center for Integrated Nanotechnologies (CINT), Technical Staff Member Scientist 5 (2015-present)
Los Alamos National Laboratory, Materials Physics & Applications Division, CINT, Technical Staff Member Scientist 4 (2010-2015)
Los Alamos National Laboratory, Chemistry Division and CINT, Technical Staff Member (2006-2010)
Los Alamos National Laboratory, Chemistry Division, Technical Staff Member (2001-2006)

Publications (10 recent or highly cited out of >85; >7800 citations; H-index 37)

1. Orfield, N. J., McBride, J. R., Wang, F.; Buck, M. R., Keene, J. D., Reid, K. R., Htoon, H.,* Hollingsworth, J. A.,* Rosenthal, S. J.* (*co-corresponding) Quantum Yield Heterogeneity Among Single Nonblinking Quantum Dots Revealed by Atomic Structure-Quantum Optics Correlation. *ACS Nano* **2016**, *10*, 1960-1968.
2. Hollingsworth, J. A., Htoon, H., Piryatinski, A., Götzinger, S., Sandoghdar, V. When excitons and plasmons meet: Emerging function through synthesis and assembly. Invited Review *MRS Bull*. **2015**, *40*, 768.
3. Acharya, K. P., Nguyen, H. M., Paulite, M., Piryatinski, A., Zhang, J., Casson, J. L., Xu, H., Htoon, H. & Hollingsworth, J. A. Elucidation of Two Giants: Challenges to Thick-shell Synthesis in CdSe/ZnSe and ZnSe/CdS Core/Shell Quantum Dots. *J. Am. Chem. Soc*. **2015**, *137*, 3755-3758.
4. Karan, N. S., Keller, A. M., Sampat, S., Roslyak, O., Arefin, A., Hanson, C. J., Casson, J. L., Desireddy, A., Ghosh, Y., Piryatinski, A., Iyer, R. , Htoon, H., Malko, A. V. & Hollingsworth, J. A., Plasmonic Giant Quantum Dots: Hybrid Semiconductor-Metal Nanostructures for Truly Simultaneous Optical Imaging, Photothermal Effect and Thermometry. *Chem. Sci*. **2015**, *6*, 2224-2236.
5. Acharya, K. P; Ji, Z.; Holesinger, T. G.; Crisp, J. A.; Ivanov, S. A.; Sykora, M.; Hollingsworth, J. A. Layer-by-Layer Fabrication of Nanowire Sensitized Solar Cells: Geometry-Independent Integration. *Adv. Funct. Mater*. **2014**, *24*, 6843-6852.
6. Laocharoensuk, R.; Palaniappan, K.; Smith, N. A.; Dickerson, R. M.; D. Werder, Baldwin, J. K.; Hollingsworth, J. A. Flow-based solution–liquid–solid nanowire synthesis, *Nature Nanotechnology* **2013** *8*, 660-666. (Highlighted in *NPG Asia Materials*.)
7. Dennis, A. M.; Mangum, B.; Piryatinski, A.; Park, Y.-S.; Hannah, D.; Casson, J.; Williams, D.; Schaller, R.; Htoon, H.; Hollingsworth, J. A. Suppressed Blinking and Auger Recombination in Near-Infrared Type-II InP/CdS Nanocrystal Quantum Dots. *Nano Lett*. **2012** *12*, 5545-5551.
8. Ghosh, Y.; Mangum, B.D.; Casson, J. L.; Williams, D. J.; Htoon, H.; Hollingsworth, J. A. New Insights into the Complexities of Shell Growth and the Strong Influence of Particle Volume in Non-Blinking "Giant" Core/Shell Nanocrystal Quantum Dots. *J. Am.*

Chem. Soc. **2012**, *134*, 9634–9643.
9. Pietryga, J. M.; Werder, D. J.; Williams, D. J.; Casson, J. L.; Schaller, R. D.; Klimov, V. I., and Hollingsworth, J. A. Utilizing the lability of lead selenide to produce heterostructured nanocrystals with bright, stable infrared emission. *J. Am. Chem. Soc.* **2008**, *130*, 4879-4885
10. Chen, Y.; Vela, J.; Htoon, H.; Casson, J. L.; Werder, D. J.; Bussian, D. A.; Klimov, V. I., and Hollingsworth, J. A., "Giant" multishell CdSe nanocrystal quantum dots with suppressed blinking. *J. Am. Chem. Soc.* **2008**, *130*, 5026-5027.

Awards and Synergistic Activities

Awards:

LANL Program Recognition Award and LANL Achievement Award (2014)
LANL Fellows' Prize for Research (2013)
LANL Associate Directorate for Chemistry, Life, & Earth Sciences Achievement Award (2009)
LANL Awards for Outstanding Scientific Achievement (2010, 2006, 2001)
LANL Women's Career Development Mentoring Award (2005)
LANL Distinguished Postdoctoral Performance Award (Small Team) (2002)
LANL Director's Postdoctoral Fellow (1999-2001)
NASA Graduate Student Researchers Program Center Fellow (1996-1999)
MRS Graduate Student Award Finalist (Fall, 1997)
Phi Beta Kappa (1992-present)
National Merit Scholarship, Grinnell College (1988-1992)
Three awarded US Patents: 7,935,419 (2011): "Thick-shell Nanocrystal Quantum Dots; 7,261,940 (2007): "Multifunctional Nanocrystals; 6,819,692 (2004): "Optical amplifiers and lasers"

Activities:

>45 invited talks and seminars since 2007
Councilor, ACS Colloid and Surface Science Division (2016-2018; national elected position)
CINT Nanowire Integration Focus Area: Science Leader (2010-2015)
CINT Nanophotonics & Optical Nanomaterials (NPON) Thrust: Acting Science Partner Leader (2013 completed)
Program Committee Member/Chair: LANL Center for Nonlinear Studies (CNLS) Executive Committee Member (2013-present), LANL Director's Colloquium Selection Committee Member/Chair (Member: 2011-2013; Chair: 2013-present), LANL Fellows Screening Committee Member (2011), SPIE Photonics West QDs for Biomedical Applications (2007 to present) and 26th Rare Earth Research Conference (2011).
Chair and organizer: Center for Nonlinear Studies (CNLS) 2014 Annual Conference: Mesoscale Science. CINT 2008 Workshop on Semiconductor Nanowires and CINT 2012 Workshop on Advances at the Interface of Biology and Nanomaterials. Founding Member: CINT Nanowire Working Group (2008; ongoing). Chair: LANL Laboratory Directed Research & Development Chemistry Exploratory Research Committee Chair (2007-2009). Co-organizer: CLEO Workshop on Nanophotonics Research at the DOE Nanoscale Science Research Centers.
Invited Expert Presenter/Contributor to National Planning Initiatives: NSF Third Workshop on Future Directions of Solid-State Chemistry (2007), ARPA-E Rare Earth and Critical Materials Workshop (2010), DOE Solid-State Lighting R&D Workshop (2012), DOE Joint (BES/EERE) Solid State Lighting Roundtable on

Science Challenges (2011, 2014, 2015), NIST Advancing Nanoparticle Manufacturing Workshop (2015).

Guest Co-Editor: Chemistry of Materials Special Issue: Synthetic and Mechanistic Advances in Nanocrystal Growth

Technical reviewer for: Molecular Foundry DOE Nanoscale Science Research Center (Berkeley), DOE Early Career Research Program (2010-2016), NIH, NSF, Canada Foundation for Innovation (2014), LANL LDRD Program, as well as Journal of the American Chemical Society, Nano Letters, ACS Nano, Angewandte Chemie, Small, The Journal of Physical Chemistry, Chemistry of Materials, Nanotechnology, Langmuir, Solid State Communications, Nature Communications, Nature Materials, Nature Nanotechnology, etc.

Collaborators (last 4 years):

S. Anderson (Un. Utah), S. Brock (Wayne St.), Y. Chabal (UT Dallas), A. M. Dennis (Boston Un.), S. Götzinger (Max Planck Institute for the Science of Light), F. Gu (Un. Waterloo), L. Lauhon (NW Un.), X. Li (UT Austin), D. Lidke (UNM), H. Luo (NMSU), A. Malko (UT Dallas), J. R. McBride (Vanderbilt Un.), P. Nagpal (UC Boulder), S. J. Rosenthal (Vanderbilt Un.), O. Roslyak (Fordham Un.), V. Sandoghdar (Max Planck Institute for the Science of Light), S. Sampat (UT Dallas), R. Schaller (ANL/NWU), E. Serrano (NMSU), M. Stewart (NRL), Z. Wang (Cornell Un.), B. S. Wilson (UNM), S. X. Zhang (Indian Un.)

Graduate and Postdoctoral Advisors:

William E. Buhro (Washington Un. in St. Louis)
Victor I. Klimov (LANL)

Thesis Advisor and Postgraduate – Scholar Sponsor (last 5 years):

Graduate Students:
- Christina Hanson (UNM)
- Peter Schulz (Un. Utah)

Postdoctoral Researchers:
- Somak Majumder, LANL
- Genqiang Zhang, LANL (co-mentor)
- Sachi K (UT Dallas) (co-mentor)
- Nimai Mishra, LANL
- Matthew Buck, LANL (co-mentor)
- Farah Dawood, LANL
- Krisha Acharya, LANL
- Niladri Karan, LANL
- Allison Dennis, LANL
- Yagnaseni Ghosh, LANL
- Rawiwan Laocharoensuk, LANL
- Kumar Palaniappan, LANL
- Andrea Steinbrück, LANL
- Janardan Kundu, LANL
- Aaron Keller, LANL (co-mentor)

15 Postdocs, 2 graduate students, 3 undergraduate students, 4 high school students

SERGEI A. IVANOV

Staff Scientist
Nanophotonics and Optical Nanomaterials
Center for Integrated Nanotechnologies
Los Alamos National Laboratory
Los Alamos, NM 87545

Phone: 505-284-7971
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Email: ivanov@lanl.gov

Education

BS/MS 1996 Moscow State University, Russia;
Ph. D. 2002, University of Wisconsin-Madison;

Professional Experience

2006 --- Technical Staff Member, Center for Integrated Nanotechnologies, Los Alamos National Laboratory
2004-2005 Postdoctoral Researcher, Los Alamos National Laboratory
2002-2004 Postdoctoral Fellow, Los Alamos National Laboratory

Selected Publications

K. Ramasamy, R. Gupta, S. Palchoudhury, S. A. Ivanov, A. Gupta "Layer-Structured Copper Antimony Chalcogenides ($CuSbSe_xS_{2-x}$): Stable Electrode Materials for Supercapacitors" Chem. Mater. 27(1), 379 (2015).

K. Ramasamy, P. G. Kotula, A. F. Fidler, J. M. Pietryga, S. A. Ivanov "Sn_xGe_{1-x} Alloy Nanocrystals: A First Step Toward Solution-Processed Group IV Photovoltaics" Chem. Mater. 27(13), 4640 (2015).

A. M. Karim, N. Al-Hasan, S. A. Ivanov, S. Siefert, R. Kelly, A. Benavidez, L. Kovarik, A. R. Jenkins, A. K. Datye "Synthesis of 1nm Monodisperse Pd Nanoparticles: Understanding the Synthesis Mechanism by *in situ* XAFS and SAXS in a Microfluidic Reactor" J. Phys. Chem. C 119(23), 13257 (2015).

S. Goel, K. A. Velizhanin, A.Piryatinski, S. A. Ivanov, S. Tretiak "Ligand Effects on Optical Properties of Small Gold Clusters: A TDDFT study" J. Phys. Chem. C 116(5), 3242 (2012).

S.A. Fisher, A. M. Crotty, S. V. Kilina, S. A. Ivanov, S. Tretiak "Passivating Ligand and Solvent Contributions to the Electronic Properties of Semiconductor Nanocrystals" Nanoscale 4, 940 (2012).

S. A. Ivanov, I. Arachchige, C. Aikens "Density Functional Analysis of Geometries and Electronic Structures of Gold-Phosphine Clusters. The Case of $Au_4(PR_3)_4^{2+}$ and Au4(μ_2-I)$_2$(PR$_3$)$_4$." J. Phys. Chem. C 115(27), 8017 (2011).

V.V. Albert, S. A. Ivanov, S. Tretiak, S. V. Kilina "Electronic Structure of Ligated CdSe Clusters: Dependence on DFT Methodology." J. Phys. Chem. C 115(32), 15793 (2011).

Arachchige, R. Soriano, C. D. Malliakas, S. A. Ivanov, M. Kanatzidis "Amorphous and Crystalline GeTe Nanocrystals" Adv. Func. Mater. 21(14), 2737 (2011).

S. Goel, K. A. Velizhanin, A.Piryatinski, S. Tretiak, and S. A. Ivanov DFT studies of ligand binding to small gold clusters. J. Phys. Chem. Lett. 1, 927 (2010).

S. Kilina, S. A. Ivanov, S. Tretiak, Effect of surface ligands on optical and electronic spectra of semiconductor nanoclusters. J. Am. Chem. Soc. 131 (22), 7717 (2009).

S. A. Ivanov, A. Piryatinski, J. Nanda, S. Tretiak, K. R. Zavadil, W. O. Wallace, D. Werder, and V. I. Klimov, Type-II Core/Shell CdS/ZnSe Nanocrystals: Synthesis, Electronic Structures, and Spectroscopic Properties. J. Am. Chem. Soc. 129 (38), 11708 (2007).

J. Nanda, S. A. Ivanov, M. Achermann, I. Bezel, A. Piryatinski, and V. I. Klimov, Light amplification in the single-exciton regime using exciton-exciton repulsion in type-II nanocrystal quantum dots. J. Phys. Chem. C 111(42), 15382 (2007).

V. I. Klimov, S. A. Ivanov, J. Nanda, M. Achermann, I. Bezel, J. A. McGuire, and A. Piryatinski, Single-exciton optical gain in semiconductor nanocrystals. Nature 447, 441 (2007).

S. A. Ivanov et al., Light Amplification Using Inverted Core/Shell Nanocrystals: Towards Lasing in the Single-Exciton Regime. J. Phys. Chem. B. 108, 10625 (2004).

Piryatinski, S. A. Ivanov, S. Tretiak, and V.I. Klimov, Effect of Quantum and Dielectric Confinement on the Exciton-Exciton Interaction Energy in Type II Core/Shell Semiconductor Nanocrystals. Nano Letters 7(1), 108 (2007).

E. G. Mednikov, S. A. Ivanov, I.V. Slovokhotova, and L. F. Dahl, Nanosized $Pd_{52}(CO)_{36}(PEt_3)_{14}$ and $Pd_{66}(CO)_{45}(PEt_3)_{16}$ Clusters Based on a Hypothetical Pd38 Vertex-Truncated μ_3 Octahedron. Angew. Chem. Int. Ed., 44(42), 69848 (2005).

S. A. Ivanov, J. Nanda, A. Piryatinski, M. Achermann, L. P. Balet, I.V. Bezel, P.O. Anikeeva, S. Tretiak, and V.I. Klimov, Light Amplification Using Inverted Core/Shell Nanocrystals: Towards Lasing in the Single-Exciton Regime. J. Phys. Chem. B. 108, 10625 (2004).

Awards and Synergistic Activities

Journal reviewer: Reviewer: J. Am. Chem. Soc., J. Chem . Phys., J. Phys. Chem. C, J. Mater. Chem., J. Cluster Sci.; Inorg. Chem.; Phys. Chem.-Chem. Phys.; Angew. Chem.; Chem. Comm., Chem. Mater.;

Collaborators:

Sergei Tretiak, LANL; Victor Klimov, LANL; Dale Huber, Sandia National Lab; Svetlana Kilina, North Dakota State University; Lawrence Dahl, UW-Madison; Abhaya Datye, University of New Mexico; Ayman Karim, Pacific Northwest National Lab.

Graduate Advisors and Postdoctoral Sponsors:

Lawrence Dahl, UW-Madison

Victor Klimov, LANL

Thesis Advisor and Postgraduate-Scholar Sponsor: (over the last 5 years)

LANL postdocs Ramasamy, Karthik; Crisp, Jeffrey; Arachchige, Indika. Currently PhD co-advisor for Wenhui Li at Virginia Tech.

TING S. WILLIE LUK
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Center for Integrated Nanotechnologies Phone: 505-844-8931
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Albuquerque, NM 87185 Email: tsluk@sandia.gov

Education

Undergraduate: University of Hawaii, Manoa B.Sc. in Physics 1972
Graduate: State University of New York at Stony Brook Ph.D. in Physics 1981
Thesis Advisor: Prof. Harold Metcalf

Professional Experience

CINT scientist, 2008-present
Principal Member of Technical Staff, Sandia National Laboratories, 1999-present
Contractor, Sandia National Laboratories, 1998-1999
Assistant Professor of Physics, U. of Wyoming, 1994-1999
Research Professor, University of Illinois at Chicago, 1982-1994
Postdoctoral research, University of Illinois at Chicago, 1981-1982

Selected Publications

S. Campione, J. R. Wendt, G. A. Keeler, and T. S. Luk, "Near-Infrared Strong Coupling between Metamaterials and Epsilon-near-Zero Modes in Degenerately Doped Semiconductor Nanolayers," ACS Photonics (2016).

M. Zhou, S. Yi, T. S. Luk, Q. Gan, S. Fan, and Z. Yu, "Analog of superradiant emission in thermal emitters," Phys Rev B **92** (2015).

J. Zeng, J. Gao, T. S. Luk, N. M. Litchinitser, and X. Yang, "Structuring Light by Concentric-Ring Patterned Magnetic Metamaterial Cavities," Nano Letters (2015).

T. S. Luk, D. de Ceglia, S. Liu, G. A. Keeler, R. P. Prasankumar, M. A. Vincenti, M. Scalora, M. B. Sinclair, and S. Campione, "Enhanced third harmonic generation from the epsilon-near-zero modes of ultrathin films," Applied Physics Letters **106**, 151103 (2015).

D. Jin, Q. Hu, D. Neuhauser, F. von Cube, Y. Yang, R. Sachan, T. S. Luk, D. C. Bell, and N. X. Fang, "Quantum-Spillover enhanced surface-plasmonic absorption at the interface of Silver and high-index dielectrics," (2015).

F. Cheng, J. Gao, T. S. Luk, and X. Yang, "Structural color printing based on plasmonic metasurfaces of perfect light absorption," Sci. Rep. **5** (2015).

S. Campione, T. S. Luk, S. Liu, and M. B. Sinclair, "Optical properties of transiently-excited semiconductor hyperbolic metamaterials," Optical Materials Express **5**, 2385-2394 (2015).

T. S. Luk, S. Campione, I. Kim, S. Feng, Y. C. Jun, S. Liu, J. B. Wright, I. Brener, P. B. Catrysse, S. Fan, and M. B. Sinclair, "Directional perfect absorption using deep subwavelength low-permittivity films," Physical Review B **90**, 085411 (2014).

Y. C. Jun, T. S. Luk, A. R. Ellis, J. F. Klem, and I. Brener, "Doping-tunable thermal emission from plasmon polaritons in semiconductor epsilon-near-zero thin films," Applied Physics Letters **105** (2014).

C. Guclu, T. S. Luk, G. T. Wang, and F. Capolino, "Radiative emission enhancement using nano-antennas made of hyperbolic metamaterial resonators," Applied Physics Letters **105**, - (2014).

Awards and Synergistic Activities

Honors

- Fellow of the Optical Society of America (1994)

Collaborators: S.R. Brueck, U. of New Mexico; Zongfu Yu, U. of Wisconsin; Qiaoqiang Gan, U. of Buffalo; Natalia M. Litchinitser, U. of Buffalo; Shanhui Fan, Stanford University; Antonio Hurtado, University of Strathclyde; Y. Kivshar, The Australian National University; Dragomir N. Neshev, The Australian National University; Xiaodong Yang, Missouri University of Science and Technology; Jie Gao, Missouri University of Science and Technology; N.X. Fang, MIT; Domenico de Ceglia, AMRDEC; Maria A. Vincenti, AMRDEC; Michael Scalora, AMRDEC; Staude Isabelle, University of Jena; Young Chul Jun, Ulasan National Institute of Science and Technology; Filippo Capolino, U. of California Irvine; Iltai Kim, U of Texas Corpus Christi;

Graduate and Postdoctoral Advisors: Harold Metcalf, Department of Physics, State University of New York at Stony Brook; Charlie K. Rhodes, Department of Physics, University of Illinois at Chicago

Thesis Advisor and Postgraduate –Postdocs: Iltai Kim, U. of Texas Corpus Christi, total: 1.

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Education

B. S. University of Texas at Austin, Electrical Engineering, May 1997
M. S. Massachusetts Institute of Technology, Electrical Engineering, September 1999
Ph. D. Massachusetts Institute of Technology, Electrical Engineering, May 2003
Postdoc: Los Alamos National Laboratory, Materials Science and Technology, Aug. 2003-Feb. 2006

Professional Experience

Feb. 2006-present: Technical Staff Member, Center for Integrated Nanotechnologies (CINT), LANL
Nov. 2008-present: Adjunct Assistant Professor, University of New Mexico
June 2009-March 2010: Acting Partner Scientific Leader, Nanophotonics Thrust, CINT, LANL

Selected Publications

Y. Dai, J. Bowlan, H. Li, H. Miao, Y. G. Shi, S. A. Trugman. J.-X. Zhu, H. Ding, A. J. Taylor, D. A. Yarotski, and R. P. Prasankumar, "Ultrafast carrier dynamics in the large magnetoresistance material WTe_2," Phys. Rev. B (Rapid Comm.) 92, 161104(R) (2015)

J. Lee, S. A. Trugman, C. L. Zhang, X. S. Xu, S.-W. Cheong, C. D. Batista, D. A. Yarotski, A. J. Taylor, and R. P. Prasankumar, "The influence of charge and magnetic order on polaron and acoustic phonon dynamics in $LuFe_2O_4$," Appl. Phys. Lett. 107, 042906 (2015).

Y.-M. Sheu, S. A. Trugman, L. Yan, Q. X. Jia, A. J. Taylor, and R. P. Prasankumar, "Ultrafast all-optical manipulation of interfacial-magnetoelectric coupling," Nature Communications 5, 5832 (2014)

J. Qi, T. Durakiewicz, S. A. Trugman, J.-X. Zhu, P. S. Riseborough, R. Baumbach, E. D. Bauer, K. Gofryk, J.-Q. Meng, J. J. Joyce, A. J. Taylor,, and R. P. Prasankumar, "Revealing multiple gaps in the electronic structure of USb_2 using femtosecond optical pulses", Phys. Rev. Lett. 111, 057402 (2013)

M. A. Seo, J. Yoo, S. A. Dayeh, S. T. Picraux, A. J. Taylor, and R. P. Prasankumar, "Mapping carrier diffusion in single silicon core-shell nanowires with ultrafast optical microscopy," Nano Lett. 12, 6334 (2012),

Y.-M. Sheu, S. A. Trugman, Y.-S. Park, S. Lee, H. Y. Yi, S.-W. Cheong, Q. X. Jia, A. J. Taylor, and R. P. Prasankumar, "Ultrafast carrier dynamics and radiative recombination in multiferroic $BiFeO_3$," Appl. Phys. Lett. 100, 242904 (2012),

R. P. Prasankumar and A. J. Taylor (editors) Optical Techniques for Solid-State Materials Characterization. Taylor & Francis, Boca Raton, FL (2011).

(invited review paper) R. P. Prasankumar, Prashanth C. Upadhya, and A. J. Taylor, "Ultrafast carrier dynamics in semiconductor nanowires," Physica Status Solidi (b) 246, 1973 (2009). (selected for the cover)

R. P. Prasankumar, S. G. Choi, S. A. Trugman, S. T. Picraux, and A. J. Taylor, "Ultrafast electron and hole dynamics in germanium nanowires," Nano Lett. 8, 1619 (2008).

D. J. Hilton, R. P. Prasankumar, S. Fourmaux, A. Cavalleri, D. Brassard, M. A. El Khakani, J.-C. Kieffer, A. J. Taylor, and R. D. Averitt, "Enhanced photosusceptibility near T_c for the light-induced insulator-to-metal phase transition in vanadium dioxide," Phys. Rev. Lett. 99, 226401 (2007).

(invited review paper) D. J. Hilton*, R. P. Prasankumar*, S. A. Trugman, A. J. Taylor, and R.

D. Averitt, "On photo-induced melting phenomena in complex materials: Probing quasiparticle dynamics using infrared and far-infrared pulses," J. Phys. Soc. Jpn 75, 011006 (2006). (*both authors contributed equally to this work)

R. P. Prasankumar, H. Okamura, H. Imai, Y. Shimakawa, Y. Kubo, A. J. Taylor, and R. D. Averitt, "Coupled charge-spin dynamics in the magnetoresistive pyrochlore $Tl_2Mn_2O_7$ probed by ultrafast mid-infrared spectroscopy," Phys. Rev. Lett. 95, 267404 (2005).

R. P. Prasankumar, A. Scopatz, D. J. Hilton, A. J. Taylor, R. D. Averitt, J. Zide, and A. C. Gossard, "Carrier dynamics in self-assembled ErAs nanoislands embedded in GaAs measured by optical pump-THz probe spectroscopy," Appl. Phys. Lett. 86, 201105 (2005).

Awards and Synergistic Activities

- Served on several LANL proposal review committees (2008-2013) and CINT internal job selection committees (2009, 2012)
- Co-organizer and session chair, NSRC Nanophotonics Symposium, part of CLEO (2013)
- Co-organizer, "Quantum and Dirac Materials for Energy Applications Conference," 2015.
- Lead organizer, Symposium WW "Ultrafast dynamics in complex functional materials," MRS Spring Meeting 2015.
- Member of organizing committee for International Year of Light event at UNM (2015)
- CLEO Optical Interactions with Condensed Matter and Ultrafast Phenomena subcommittee member (2012-14); chair (2015-16)
- APS-Division of Laser Science representative for the Joint Council on Quantum Electronics and voting member of CLEO Steering Committee (2014-)
- Member of proposal evaluation board for Center for Nanoscale Materials, Argonne National Laboratory (2015-2017)
- Session chair, CLEO (2008, 2013, 2015); Ultrafast Phenomena (2012); MS&T (2013); MRS (2014, 2015); SPIE Photonics West (2016)
- Reviewer for several journals, including Nature Physics, Nature Communications, Phys. Rev. Lett., Nano. Lett., ACS Nano, Laser & Photonics Reviews, Appl. Phys. Lett., Scientific Reports, Phys. Rev. B, Opt. Express, Opt. Lett., New J. Physics, J. Appl. Phys., Euro. Phys. Lett., Photon. Tech. Lett., Nanoscale Research Lett., Chem. Phys. Lett., J. Chem. Phys., MRS Comm.
- Reviewer for DOE office of Basic Energy Sciences (BES), NIH, SLAC, ARO

Collaborators (last 48 months):

R. D. Averitt, Boston University, Boston, MA; C. D. Batista, Los Alamos National Laboratory, Los Alamos, NM; S. R. J. Brueck, University of New Mexico, Albuquerque, NM; S.-W. Cheong, Rutgers University, Piscataway, NJ; J. Davis, Swinburne University of Technology, Melbourne, Australia; S. A. Dayeh, University of California at San Diego, San Diego, CA; H. Ding, Chinese Academy of Sciences, Beijing, China; T. Durakiewicz, Los Alamos National Laboratory, Los Alamos, NM; R. F. Haglund, Vanderbilt University, Nashville, TN; D. J. Hilton, University of Alabama-Birmingham, Birmingham, AL; Q. X. Jia, Los Alamos National Laboratory, Los Alamos, NM; S. Krishna, University of New Mexico, Albuquerque, NM; Ting Shan Luk, Sandia National Laboratories, Albuquerque, NM; S. Oh, Rutgers University, Piscataway, NJ; X. G. Qiu, Chinese Academy of Sciences, Beijing, China; A. D. Mohite, Los Alamos National Laboratory, Los Alamos, NM; T. C. Sum, Nanyang Technological University, Singapore; B. S. Swartzentruber, Sandia National Laboratories, Albuquerque, NM; D. Talbayev, Tulane University, New Orleans, LA; A. J. Taylor, Los Alamos National Laboratory, Los Alamos, NM; S. A. Trugman, Los Alamos National Laboratory, Los Alamos, NM; G. T. Wang, Sandia National Laboratories, Albuquerque, NM; J.-X. Zhu, Los Alamos National Laboratory, Los Alamos, NM

Graduate and Postdoctoral Advisors: James G. Fujimoto (Massachusetts Institute of Technology); Richard D. Averitt, Antoinette J. Taylor (LANL)

Thesis Advisor and Postgraduate – Scholar Sponsor: Former postdocs**:** Prashanth Upadhya, Indian Space Research Organization; Keshav Dani, Okinawa Institute of Science and Technology; Jinho Lee, Gyeongsang National University; Min Ah Seo, Korea Institute of Science and Technology; Jingbo Qi, PEAC Institute of Multiscale Sciences; Stephane Boubanga Tombet, Tohoku University; Rolando Valdes Aguilar, Ohio State University; Yu-Miin Sheu, Chiao Tung University (winner of 2015 Postdoctoral Publication Prize in Experimental Sciences), John Bowlan, LANL.
Current**:** Pamela Bowlan (LANL Director's postdoctoral fellow), Brian McFarland (LANL Director's postdoctoral fellow), Kamaraju Natarajan, Yaomin Dai, Michael Williams.
(Total: 14 postdocs)

9.0 Other Support of Investigators and Collaborators

STEPHEN K. DOORN

Project Title: Quantum Optics of Solitary Dopants in Carbon Nanotubes
Funding Agency: Los Alamos National Laboratory LDRD
Total Funding: $350K/yr
Duration: FY16-FY18
Role: co-PI
Level of Effort: 0.25 FTE
Project Scope: Study and control the quantum optical properties of novel solitary covalent dopant states in carbon nanotubes towards applications as room temperature single photon emitters.

Investigator: Igal Brener	Other Agencies to which this proposal has been/will be submitted: N/A
Support (Current, Pending, Submission Planned in Future or Transfer of Support): Current	
Project/Proposal Title and grant number, if appropriate: *Light-matter interaction phenomena using subwavelength engineering of material properties*	
Source of Support: Office of Basic Energy Sciences, DOE	Location of Project: Sandia National Laboratories
Annual Award Amount: $950,000	Total Award Period Covered: 8/2014 - present
Annual Award Amount to PI's Research: $	
Person-Months Per Year Committed to Project: __2__ Pers. Months; Specify: Calendar	
Describe Research Including Synergies and Delineation with Respect to this Proposal/Award: The goal of this project is to achieve fundamental understanding and control of light– matter interaction through engineering material properties at the subwavelength scale. Our approach involves the use of localized and propagating metamaterial photon modes coupled to semiconductor heterostructures.	
Investigator: Igal Brener (Sinclair, PI)	Other Agencies to which this proposal has been/will be submitted: N/A
Support (Current, Pending, Submission Planned in Future or Transfer of Support): Pending	
Project/Proposal Title and grant number, if appropriate: *A New All-Dielectric Nanolaser*	
Source of Support: Laboratory Directed Research and Development	Location of Project: Sandia National Laboratories, Albuquerque, NM
Annual Award Amount: $ 250K	Total Award Period Covered: FY16-FY18
Annual Award Amount to PI's Research: $45K	
Person-Months Per Year Committed to Project: _1___ Pers. Months; Specify: Calendar	
Describe Research Including Synergies and Delineation with Respect to this Proposal/Award: The cope of the project is to create a nanolaser using Fano resonances in all-dielectric metamaterials. There could be some synergy with the BES program since we have interest in similar structures in the context of the physics of light matter interaction.	
Investigator: Igal Brener (David Peters, PI)	Other Agencies to which this proposal has been/will be submitted: N/A
Support (Current, Pending, Submission Planned in Future or Transfer of Support): Pending	

Project/Proposal Title and grant number, if appropriate: *Smart Sensor Technologies*	
Source of Support: Laboratory Directed Research and Development	Location of Project: Sandia National Laboratories, Albuquerque, NM
Total Award Amount: $12,000	Total Award Period Covered: FY16-F18
Total Award Amount to PI's Research: $100K	
Person-Months Per Year Committed to Project: _3_ Pers. Months; Specify: Cal	
Describe Synergies and/or Overlaps with This Proposal/Award: The scope is to develop a smart infrared pixel based on metasurfaces coupled to III-V semiconductors. This is an applied project and there is some synergy since the materials and samples are synergistic.	
Investigator: Igal Brener (Igal Brener, PI)	Other Agencies to which this proposal has been/will be submitted: N/A
Support (Current, Pending, Submission Planned in Future or Transfer of Support): Current	
Project/Proposal Title and grant number, if appropriate: *A Compact, Spectrally-Tunable Source of Entangled Photon-Pairs for Quantum Sensing*	
Source of Support: Laboratory Directed Research and Development	Location of Project: Sandia National Laboratories, Albuquerque, NM
Total Award Amount: $1.2M	Total Award Period Covered: FY16-F18
Total Award Amount to PI's Research: $100K	
Person-Months Per Year Committed to Project: _3_ Pers. Months; Specify: Cal	
Describe Synergies and/or Overlaps with This Proposal/Award: This project aims at developing enhanced nonlinearities using intersubband transitions coupled to metamaterials, and observing spontaneous parametric downconversion.	

RYAN CAMACHO

Project Title:	Timing Authentication Secured by Quantum Correlations
Funding Agency:	DARPA
Total Funding:	$100k/yr
Duration:	FY15-FY17
Role:	PI
Level of Effort:	0.05 FTE
Project Scope:	Develop microresonators for quantum zeno switching

Project Title:	Quiness: Macroscopic Quantum Communications
Funding Agency:	DARPA
Total Funding:	$480k/yr
Duration:	FY13-present
Role:	PI
Level of Effort:	0.05 FTE
Project Scope:	Develop quantum silicon photonic technologies for QKD

Project Title:	SECANT QKD
Funding Agency:	Sandia National Laboratory LDRD
Total Funding:	$4.7M/yr
Duration:	FY14-FY16
Role:	PI
Level of Effort:	0.4 FTE
Project Scope:	Develop chip-scale quantum key distribution components

HOU-TONG CHEN

Project Title:	Ultra light and Extremely Compact Metamaterial Lens Antenna
Funding Agency:	NRO DII
Total Funding:	$400K
Duration:	FY15-FY16
Role:	Co-Investigator
Level of Effort:	0.05 FTE
Project Scope:	Develop microwave metamaterial lens Antenna

Project Title:	Meso-Photonic Materials for Tailored Light-Matter Interactions
Funding Agency:	Los Alamos National Laboratory LDRD
Total Funding:	$5M
Duration:	FY15-FY17
Role:	PI
Level of Effort:	0.5 FTE
Project Scope:	Develop meso-photonic structures and integrate functional materials for novel photonic functionality

Investigator: A. Efimov (A. J. Taylor)	Other Agencies to which this proposal has been/will be submitted:
Support (Current, Pending, Submission Planned in Future or Transfer of Support): Current	
Project/Proposal Title and grant number, if appropriate: Flat Microwave Metamaterial Lens Antenna	
Source of Support: DII Location of Project: LANL	
Annual Award Amount: $400K Total Award Period Covered: 10/15-10/16	
Annual Award Amount to PI's Research: $192K	
Person-Months Per Year Committed to Project: 6C Pers. Months; Specify: Cal., Acad., or Sumr:	
Describe research including synergies and/or overlaps with This Proposal/Award: Develop an efficient flat flexible metamaterial lens antenna at microwave frequencies	

HAN HTOON

Project Title: "Giant" Nanocrystal Quantum Dots: Controlling Charge Recombination Processes for High-Efficiency Solid-State Lighting

Funding Agency:	Department of Energy/Office of Science (Basic Energy Sciences)
Total Funding:	$ 660 K/yr
Duration:	FY09-present
Role:	Co-PI
Level of Effort:	0.2 FTE

Project Scope: Investigation of giant nanocrystal quantum dot for high efficiency solid state lighting.

Project Title: Quantum Optics of Solitary Covalent Dopants in Carbon Nanotubes
Funding Agency: LDRD, LANL
Total Funding: $ 350 K/yr
Duration: FY16-present
Role: PI
Level of Effort: 0.15 FTE
Project Scope: To investigate quantum optical properties of solitary dopant states in carbon nanotubes for quantum information technology applications.

Project Title: Next-Generation "Giant" Quantum Dots: Performance-Engineered for Lighting"
Funding Agency: Office of Energy Efficiency and Renewable Energy (EERE)
Total Funding: $ 500K/yr
Duration: FY16-present
Role: PI
Level of Effort: 0.15 FTE
Project Scope: To develop "giant" quantum dot based red emitting down converter for white light LED.

JENNIFER HOLLINGSWORTH
Project Title: “Giant” Nanocrystal Quantum Dots: Controlling Charge Recombination Processes for High-Efficiency Solid-State Lighting
Funding Agency: DOE BES
Total Funding: $2.6M
Duration: 2013-2016
Role: co-PI
Level of Effort: 0.20 FTE
Project Scope: Fundamental physics and chemistry of “giant” quantum dots toward applications in solid-state lighting; new functional materials development

Project Title: Metal and Semiconductor Nanocrystal Superlattices Under Pressure: Multiscale Tuning of Structure and Function (20140456ER)
Funding Agency: Los Alamos National Laboratory LDRD
Total Funding: $1.15 M
Duration: 2014-2016
Role: PI
Level of Effort: 0.05 FTE
Project Scope: Explore pressure-tuning as a novel approach to creating emergent functionality in mixed semiconductor-metal self-assembled systems.

Project Title: Precision ‘Bottom-Up’ Fabrication of Non-classical Photon Sources (20150604ER)
Funding Agency: Los Alamos National Laboratory LDRD
Total Funding: $1.0 M
Duration: 2015-2017
Role: PI
Level of Effort: 0.05 FTE
Project Scope: Developing nanoscale additive manufacturing approach to creating novel single-photon sources from quantum dot/metal-oxide nanowire –waveguides hybrids.

Project Title: Near-unity, Stable, Scalable Down-conversion of High-power Light Sources (20160357ER)
Funding Agency: Los Alamos National Laboratory LDRD
Total Funding: $0.63 M
Duration: 2016-2017
Role: co-Investigator
Level of Effort: 0.05 FTE
Project Scope: Investigating new stable green-emitting quantum dots for solid-state lighting and effects of field and/or charging on photoluminescence spectral stability and broadening as a function of device engineering.

Project Title: "Giant" Nanocrystal Quantum Dots: Controlling Charge Recombination Processes for High-Efficiency Solid-State Lighting (M615002955)
Funding Agency: DOE EERE managed by DOE-NETL
Total Funding: $1.0 M
Duration: 2016-2017
Role: co-PI
Level of Effort: 0.15 FTE
Project Scope: Applied research program to advance red-emitting giant quantum dots as down-conversion phosphors for efficient, stable and high quality white-light sources, targeting challenges of temperature sensitivity, long-term stability and bright/narrowband red emission.

SERGEI A. IVANOV
Project Title: Direct-gap Group-IV Nanocrystals: Cheap, Versatile Materials for Solar Cells
Funding Agency: Los Alamos National Laboratory LDRD
Total Funding: $350/yr
Duration: FY14-FY16
Role: PI
Level of Effort: 0.40 FTE
Project Scope: Synthesis and photophysics of Ge-Sn and Si-Sn nanoalloys towards their use as active light-harvesting elements in photovoltaic devices.

TING S. LUK
Project Title: Light-matter interaction phenomena using subwavelength engineering of material properties
Funding Agency: DOE Basic Energy Science
Total Funding: $ 1.05 M/yr
Duration: FY15-present
Role: Co-I
Level of Effort: 0.15 FTE
Project Scope: Light-matter interaction of hyperbolic and epsilon-near-zero materials

Project Title: Active Plasmonics from Weak to Strong Coupling Regime
Funding Agency: Sandia National Laboratories LDRD
Total Funding: $ 700 K/yr
Duration: FY13-15
Role: Co-I
Level of Effort: 0.1 FTE

Project Scope:	Near-field characterization of plasmonic structures

Project Title:	Electrically injected UV-Visible Nanowire Lasers
Funding Agency:	Sandia National Laboratories LDRD
Total Funding:	$ 500 K/yr
Duration:	FY13-15
Role:	Co-I
Level of Effort:	0.1 FTE
Project Scope:	Characterize GaN and InGaN nano-wire lasers by optical or electrical pumping.

Project Title:	Polarization exploitation of taggant remote observables
Funding Agency:	Office of Defense Nuclear Nonproliferation R&D
Total Funding:	$ 1 M/yr
Duration:	FY13-15
Role:	Co-I
Level of Effort:	0.1 FTE
Project Scope:	Characterize thin films with ellipsometer.

Investigator: Rohit Prasankumar (Wei Pan, PI)	Other Agencies to which this proposal has been /will be submitted: N/A
Support (Current):	
Project/Proposal Title and grant number, if appropriate: Quantum Electronic Phenomena and Structures	
Source of Support: DOE BES MS&E	Location of Project: LANL
Annual Award Amount: $140K	Total Award Period Covered: 10/07-present
Annual Award Amount to PI's Research: $140K	
Person-Months Per Year Committed to Project: 1.5 Per. Months (**Cal**.)	
Describe research including synergies and/or overlaps with this Proposal/Award: The focus of this project is to study the physics of novel quantum electronic phenomena, induced by strong electron-electron interactions and the interplay between electron and disorder interactions, in low dimensional quantum systems. A portion of the awarded funds are used to support a postdoctoral researcher (not included in the person-months/year).	

Investigator: Rohit Prasankumar (Turab Lookman, PI)	Other Agencies to which this proposal has been /will be submitted: N/A
Support (Current):	
Project/Proposal Title and grant number, if appropriate: Information-Driven Materials Discovery and Design	
Source of Support: LANL LDRD	Location of Project: LANL
Annual Award Amount: $1.8M	Total Award Period Covered: 10/13-9/16
Annual Award Amount to PI's Research: 0.25 FTE	
Person-Months Per Year Committed to Project: 3.0 Per. Months (**Cal**.)	
Describe research including synergies and/or overlaps with this Proposal/Award: This project uses informatics to design new materials, primarily ferroelectrics and multiferroics. My part of the project utilizes second harmonic generation to characterize these materials.	

Investigator: Rohit Prasankumar (Dmitry Yarotski, PI)	Other Agencies to which this proposal has been /will be submitted: N/A

Support (Current):	
Project/Proposal Title and grant number, if appropriate: Multiferroic Response Engineering in Mesoscale Oxide Structures	
Source of Support: LANL LDRD	Location of Project: LANL
Annual Award Amount: $ 1.5M	Total Award Period Covered: 10/13-09/16
Annual Award Amount to PI's Research: 0.2 FTE	
Person-Months Per Year Committed to Project: 1.5 Per. Months (**Cal**.)	
Describe research including synergies and/or overlaps with this Proposal/Award: The goal of this project is to use ultrafast optical, THz, and x-ray spectroscopy to gain insight on the physics of magnetoelectric (ME) coupling in nanostructured multiferroic oxides, with an eventual goal of controlling ME coupling in these materials.	
Investigator: Rohit Prasankumar (PI)	Other Agencies to which this proposal has been /will be submitted: N/A
Support (Pending):	
Project/Proposal Title and grant number, if appropriate: Dynamically Controlling Microscopic Interactions in Complex Oxides	
Source of Support: LANL LDRD	Location of Project: LANL
Annual Award Amount: $325K	Total Award Period Covered: 10/16-9/19
Annual Award Amount to PI's Research: 0.20 FTE	
Person-Months Per Year Committed to Project: 2.5 Per. Months (**Cal**.)	
Describe research including synergies and/or overlaps with this Proposal/Award: This project aims to optically control microscopic interactions in complex oxides. A portion of the awarded funds will be used to support a postdoctoral researcher (not included in the person-months/year).	
Investigator: Rohit Prasankumar (PI)	Other Agencies to which this proposal has been /will be submitted: N/A
Support (Pending):	
Project/Proposal Title and grant number, if appropriate: Shedding New Light on Quantum Phenomena in Weyl and Dirac Semimetals	
Source of Support: LANL LDRD	Location of Project: LANL
Annual Award Amount: $325K	Total Award Period Covered: 10/16-09/19
Annual Award Amount to PI's Research: 0.20 FTE	
Person-Months Per Year Committed to Project: 2.5 Per. Months (**Cal**.)	
Describe research including synergies and/or overlaps with this Proposal/Award: The goal of this project is to use time-integrated and ultrafast optical spectroscopy to shed light on quantum phenomena in Weyl and Dirac semimetals. A portion of the awarded funds will be used to support a postdoctoral researcher (not included in the person-months/year).	

10.0 Budget and Budget Explanation

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ORGANIZATION Sandia National Laboratories				**Budget Page No:**	1
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Doorn, Steve (NPON Thrust Leader)				Requested Duration:	12 (FY16) (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Brener, Igal (.6 FTE)	7.20			110,120.00	
2. Camacho, Ryan (.5 FTE)	6.00			67,966.00	
3. Luk, Ting Willie (.5 FTE)	6.00			83,032.00	
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (3) TOTAL SENIOR PERSONNEL (1-6)	19.20			261,118.00	0.00
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	12.00			91,083.00	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				352,201.00	0.00
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				128,554.00	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				480,755.00	0.00
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL				0.00	0.00
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				0.00	0.00
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				111,145.00	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				111,145.00	0.00
H. TOTAL DIRECT COSTS (A THROUGH G)				591,900.00	0.00
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				425,737.00	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				1,017,637.00	0.00
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				1,017,637.00	0.00

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ORGANIZATION Sandia National Laboratories				Budget Page No:	2
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Doorn, Steve (NPON Thrust Leader)				Requested Duration:	12 (FY17) (Months)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	by Applpicant	by DOE
1. Brener, Igal (.6 FTE)	7.20			112,979.00	
2. Camacho, Ryan (.5 FTE)	6.00			69,729.00	
3. Luk, Ting Willie (.5 FTE)	6.00			85,183.00	
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (3) TOTAL SENIOR PERSONNEL (1-6)	19.20			267,891.00	0.00
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	12.00			93,448.00	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				361,339.00	0.00
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				131,889.00	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				493,228.00	0.00
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL				0.00	0.00
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				0.00	0.00
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				113,057.00	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER				22,125.00	
TOTAL OTHER DIRECT COSTS				135,182.00	0.00
H. TOTAL DIRECT COSTS (A THROUGH G)				628,410.00	0.00
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				444,864.00	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				1,073,274.00	0.00
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				1,073,274.00	0.00

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ORGANIZATION Sandia National Laboratories				Budget Page No: 3
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Doorn, Steve (NPON Thrust Leader)				Requested Duration: 12 (F
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested
	CAL	ACAD	SUMR	by Applpicant
1. Brener, Igal (.6 FTE)	7.20			116,734.00
2. Camacho, Ryan (.5 FTE)	6.00			72,046.00
3. Luk, Ting Willie (.5 FTE)	6.00			88,014.00
4.				
5.				
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)				
7. (3) TOTAL SENIOR PERSONNEL (1-6)	19.20			276,794.00
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)				
1. (1) POST DOCTORAL ASSOCIATES	12.00			96,553.00
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)				
3. ( ) GRADUATE STUDENTS				
4. ( ) UNDERGRADUATE STUDENTS				
5. ( ) SECRETARIAL - CLERICAL				
6. ( ) OTHER				
TOTAL SALARIES AND WAGES (A+B)				373,347.00
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				136,272.00
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				509,619.00
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)				
TOTAL PERMANENT EQUIPMENT				
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				
2. FOREIGN				
TOTAL TRAVEL				0.00
F. TRAINEE/PARTICIPANT COSTS				
1. STIPENDS (Itemize levels, types + totals on budget justification page)				
2. TUITION & FEES				
3. TRAINEE TRAVEL				
4. OTHER (fully explain on justification page)				
TOTAL PARTICIPANTS ( ) TOTAL COST				0.00
G. OTHER DIRECT COSTS				
1. MATERIALS AND SUPPLIES				115,220.00
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				
3. CONSULTANT SERVICES				
4. COMPUTER (ADPE) SERVICES				
5. SUBCONTRACTS				
6. OTHER				22,504.00
TOTAL OTHER DIRECT COSTS				137,724.00

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ORGANIZATION Sandia National Laboratories				Budget Page No:	4
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Doorn, Steve (NPON Thrust Leader)				Requested Duration:	36 (FY16-18) (Months)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	by Applpicant	by DOE
1. Brener, Igal (.6 FTE)	21.60			339,834.00	
2. Camacho, Ryan (.5 FTE)	18.00			209,741.00	
3. Luk, Ting Willie (.5 FTE)	18.00			256,229.00	
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (3) TOTAL SENIOR PERSONNEL (1-6)	57.60			805,804.00	0.00
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	36.00			281,084.00	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				1,086,888.00	0.00
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				396,714.00	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				1,483,602.00	0.00
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL				0.00	0.00
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				0.00	0.00
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				339,422.00	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER				44,629.00	
TOTAL OTHER DIRECT COSTS				384,051.00	0.00
H. TOTAL DIRECT COSTS (A THROUGH G)				1,867,653.00	0.00
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				1,333,111.00	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				3,200,764.00	0.00
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				3,200,764.00	0.00

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ORGANIZATION Los Alamos National Laboratory				Budget Page No: 1	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Steve Doorn (NPON Thrust Leader)				Requested Duration: 12 (FY16) (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Doorn, Stephen (0.75FTE)	9.00			$124,177	
2. Chen, Houtong (0.50FTE)	6.00			$75,454	
3. Efimov, Anatoly (0.50FTE)	6.00			$60,227	
4. Htoon, Han (0.50 FTE)	6.00			$75,454	
5. Hollingsworth, Jennifer (0.50FTE)	6.00			$90,620	
6. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	12.00			$135,681	
7. (7) TOTAL SENIOR PERSONNEL (1-6)	45.00			$561,613	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	12.00			$76,911	
2. (1) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	6.00			$60,227	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$698,751	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$305,434	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$1,004,184	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL					
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$225,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS- University contract					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$225,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$1,229,184	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$1,268,816	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$2,498,001	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$2,498,001	

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ORGANIZATION Los Alamos National Laboratory				Budget Page No: 2	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Steve Doorn (NPON Thrust Leader)				Requested Duration: 12 (FY17) (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. Doorn, Stephen (0.75FTE)	9.00			$127,902	
2. Chen, Houtong (0.50FTE)	6.00			$77,718	
3. Efimov, Anatoly (0.50FTE)	6.00			$81,779	
4. Htoon, Han (0.50 FTE)	6.00			$77,718	
5. Hollingsworth, Jennifer (0.50FTE)	6.00			$93,339	
6. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	12.00			$139,496	
7. (7) TOTAL SENIOR PERSONNEL (1-6)	45.00			$577,951	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	12.00			$79,219	
2. (1) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	6.00			$61,779	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$718,948	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$314,248	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$1,033,196	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL — 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL					
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$250,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS- University Contract					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$250,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$1,283,196	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$1,312,472	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$2,595,668	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$2,595,668	

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(04-93)
All Other Editions Are Obsolete

U.S. Department of Energy

Budget Page

(See reverse for Instructions)

OMB Control No.
1910-1400
OMB Burden Disclosure
Statement on Reverse

ORGANIZATION Los Alamos National Laboratory				Budget Page No:	3
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Steve Doorn (NPON Thrust)				Requested Duration: 12 (FY18) (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. Doorn, Stephen (0.75FTE)	9.00			$131,739	
2. Chen, Houtong (0.50FTE)	6.00			$80,049	
3. Efimov, Anatoly (0.50FTE)	6.00			$63,632	
4. Htoon, Han (0.50 FTE)	6.00			$80,049	
5. Hollingsworth, Jennifer (0.50FTE)	6.00			$96,139	
6. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	12.00			$143,682	
7. (7) TOTAL SENIOR PERSONNEL (1-6)	45.00			$595,291	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	12.00			$81,595	
2. (1) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	6.00			$63,632	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$740,518	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$323,677	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$1,064,195	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL					
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$275,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS- University Contract					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$275,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$1,339,195	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$1,356,140	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$2,695,335	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$2,695,335	

DOE F 4620.1
(04-93)
All Other Editions Are Obsolete

U.S. Department of Energy

Budget Page

(See reverse for Instructions)

OMB Control No.
1910-1400
OMB Burden Disclosure
Statement on Reverse

ORGANIZATION Los Alamos National Laboratory				Budget Page No: 4	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Steve Doorn (NPON Thrust Leader)				Requested Duration: 36 (FY16-18) (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested	Funds Granted
	CAL	ACAD	SUMR	by Applpicant	by DOE
1. Doorn, Stephen (0.75FTE)	21.00			$383,817	
2. Chen, Houtong (0.50FTE)	18.00			$233,221	
3. Efimov, Anatoly (0.50FTE)	18.00			$185,638	
4. Htoon, Han (0.50 FTE)	18.00			$233,221	
5. Hollingsworth, Jennifer (0.50FTE)	18.00			$280,098	
6. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	36.00			$418,859	
7. (7) TOTAL SENIOR PERSONNEL (1-6)	135.00			$1,734,854	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	36.00			$237,725	
2. (1) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	18.00			$185,638	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$2,158,217	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$943,358	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$3,101,575	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL					
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$750,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$750,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$3,851,575	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				$3,937,428	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$7,789,004	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$7,789,004	

10. Budget Explanation

A. Senior Personnel

Igal Brener – (NPON Partner Science Lead) Provides scientific leadership for Thrust, provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Ryan Camacho – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Hou-Tong Chen – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Stephen Doorn – (NPON Thrust Leader) Provides scientific leadership for Thrust, provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Anatoly Efimov – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Han Htoon – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Jennifer Hollingsworth – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Sergei Ivanov – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Ting (Willie) Luk – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

Rohit Prasankumar – (CINT Scientist) Provides support for approved CINT user projects and conducts independent research in support of CINT internal science program.

B. Other Personnel

Postdoctoral Associates – Conduct research in support of CINT internal science program and work with users as appropriate to support user projects.

Other Professional – Research technologists supporting laboratory operations and instrumentation usage.

G. Other Direct Costs

1. Materials and Supplies – Laboratory supplies to support CINT Thrust user projects and internal science efforts; Thrust staff travel costs; publication costs.

6. Other (Service Contracts) – Direct costs to provide service and maintenance for the laser amplifier system.

11.0 Description of Facilities and Resources

The Nanophotonics and Optical Nanomaterials (NPON) Thrust operates several laboratory facilities in order to better understand the fundamental electrical, photonic and magnetic phenomena found in nanostructured optical materials fabricated using chemical and physical synthesis techniques. Affiliated facilities include seven laboratories at the CINT Core facility at Sandia National Laboratories (SNL), including two general nanophotonics labs, an ultrafast laser and spectroscopy lab, a laboratory for photonics-based classical and quantum information processing, chemical synthesis lab, colloidal assembly and surface templating lab and electron beam lithography lab. Additionally, NPON is supported by six laboratories at the CINT Gateway facility at Los Alamos National Laboratories (LANL), including an ultrafast optical spectroscopy and nanophotonics lab, nanoscale optical probe lab, Raman spectroscopy, microscopy, and imaging lab, laboratory for processing of carbon nanomaterials, chemical synthesis lab, and pulsed laser deposition lab. These labs include state-of-the-art synthesis, characterization and device fabrication hardware and represent significant experimental capability at both the CINT Core and Gateway. These facilities total approximately 6000 square feet of combined research space.

The ultrafast laser and spectroscopy laboratory (Core) has a broad range of capabilities for the optical characterization of materials using ultrafast sources. Optical pump/THz probe and THz time-domain spectroscopy can be performed from 0.1-15 THz. Ultrafast optical spectroscopy can be done with independently tunable pump and probe wavelengths from 267 nm-20 μm. Facilities include high sensitivity ultrafast optical microscopy, with micron spatial resolution and sub-100 fs temporal resolution. Specific instruments include a Spectra-Physics Spitfire amplifier (1 mJ, 35 fs pulses at 800nm, 1 kHz repetition rate), a KML Cascade cavity-dumped oscillator (40 nJ, 15 fs at 800nm, 2 MHz repetition rate) and a Coherent system consisting of a RegA regenerative amplifier, 9450 optical parametric amplifier (OPA) and 9850 OPA. We have recently developed a system for doing THz time-domain spectroscopy (THz-TDS) in a high magnetic field. This system is capable of measurements in a B field up to 8 T and at temperatures down to ~1.5 K, allowing us to explore novel phenomena in a wide variety of complex materials. We have also modified our system to optically photoexcite samples and measure the photoinduced changes in the transmitted THz pulse (optical-pump, THz-probe (OPTP) spectroscopy) at low temperatures and high magnetic fields; this is one of only (<5) tabletop systems with these capabilities worldwide. We envision future photoexcitation of samples with intense THz electric fields. These changes will enable us to examine the physics of a wide variety of materials (e.g., semiconductor nanostructures, 2D Dirac materials (including graphene, topological insulators, transition metal dichalcogenides) and superconductors), in previously unexplored regimes, revealing a wide range of novel physical phenomena. This lab also houses a new time-resolved PL system that consists of a femtsosecond Ti-sapphire laser tunable from 680-1040nm with a second and third harmonic generator and a pulse picker. Detection can be done using a cooled-cathode streak camera (resolution 2ps) or a fluorescence upconversion system from Ultrafast Systems (resolution ~300fs). Samples can be cooled using a closed cycle cryostat from Montana Instruments down to 2K.

The general nanophotonics labs (Core) have multiple photoluminescence setups (micro and macro) at room and low temperature, including a number of spectrometers and array detectors for UV/Visible and near infrared wavelengths. A Mid-IR time-domain spectroscopy system can be used for angle resolved transmission and reflection, amplitude and phase measurements of a variety of samples between 7 and 14 um. Additionally, thin films of IR materials can be characterized with IR variable spectroscopic ellipsometry (IR-VASE). Also these two labs have extensive instrumentation for testing of waveguide samples such as 2D photonic crystals and their interactions with quantum dots.

The laboratory for fabrication and testing of integrated photonics devices for classical and quantum information processing (Core) has been established in the last 3 years. Our current materials include both silicon and silicon nitride waveguides. We are in the process of adding lithium niobate and aluminum nitride as well. We can fabricate high quality waveguides of three varieties: conventionally etched (3-5 dB/cm), partially etched (1 dB/cm) and etchless (<1 dB/cm). We can also fabricate metal heaters (NiCr or Ti), grating couplers, distributed Bragg gratings, ring resonators, polymer spot size converters, and photonics crystals. We also have developed several additional features, including the ability to dice and polish chip edges, and multi-port fiber-chip couplers with < 1 dB of loss per facet. Finally, we have developed the capability at CINT to fabricate *in-situ* single ion detectors that can be used to accurately determine the activation yield of artificial color centers fabricated by ion implantation. In our test lab, we currently have four custom optical probe stations and a suite of lasers, single photon sources, detectors, and counters and other high speed electronics useful for a variety of quantum and classical photonics experiments. We also have the ability to fabricate fiber tapers with sub-micron diameters. Finally, we have developed close relationships with the MESA facility and can connect users to additional capabilities offered at Sandia National Labs in the area of integrated photonics and quantum information processing.

The chemical synthesis laboratory (Core) includes capabilities for organic, organometallic and inorganic synthesis and assembly of nanoscale electronic and optically active building blocks, including semiconductor quantum dots, metal nanoparticles and conjugated organic polymers. Major instruments utilized in this work include nitrogen and vacuum Schlenk lines, inert atmosphere glove boxes, 300W microwave reactor and ultrasound assisted chemical synthesis capabilities as well as a photochemistry chamber and photoluminescence and UV-Vis spectroscopy. For further characterization, thermogravimetric analysis and differential scanning calorimetry (TGA/DSC) instrumentation is available. Measurements of mass change (e.g., decomposition or sublimation temperatures) and thermal changes (often unaccompanied by the mass change as a function of temperature in such processes as melting, glass transition, second order phase transition, enthalpy and heat capacity measurements) can be made. Both techniques have become indispensible in the design of new metal precursors and understanding the structure/composition of nanocomposites.

The colloidal assembly and surface templating laboratory (Core) consists of facilities for better understanding of interparticle forces, colloidal crystal (CC) assembly and the development of tunable behavior in CCs through the use of active materials and templating. Characterization methods include measurements of particle size distribution, interparticle forces, rheology, contact angle, aggregation behavior, and optical properties. Major capabilities include Stöber sphere synthesis and rapid liquid phase nucleation facilities, DT1200 acoustic spectrometer, Haaka RS300 rheometer, and Hach turbidimeter.

The electron beam lithography laboratory (Core) provides powerful nanofabrication capabilities for a wide variety of materials and devices when combined with etch and deposition capabilities within the CINT Core Integration Laboratory. The instrument is a JEOL JBX-5FE field emission system operating at 50kV with a five inch stage. The minimum spot size is 5 nm and the minimum achievable feature size is on the order of 20 nm. Typical feature sizes are in the range of 50-250 nm. Various holders can accommodate small pieces from 5-25 mm and full wafers from 2 to 6 inches in diameter.

The ultrafast optical spectroscopy and nanophotonics laboratory (Gateway) provides a suite of ultrafast optical excitation, diagnostic and measurement capabilities, spanning wavelengths from the ultraviolet to the far-infrared, with pulse durations down to 10 fs and pulse energies up to 1 mJ. Various experimental configurations are possible, including optical pump-probe, optical pump-terahertz probe and synchronized multibeam configurations. Major hardware includes Ti:Sapphire laser amplifier systems (1 mJ / 100 fs pulses / 1 kHz and 4 μJ / 250 kHz / 800 nm), a white-light seeded parametric amplifier (sub-20 fs pulses, μJ pulse energy, 250-1000 nm), high energy femtosecond THz sources for optical pump-THz probe experiments, and XFROG and FROG systems for studying the nonlinear dynamics of ultrashort pulses in nanophotonic materials as well as a supercontinuum-based (1350-1850nm) spectral interferometry system. Additionally, the lab includes a surface-enhanced coherent antistokes Raman spectroscopy (SECARS) microscope for vibrational imaging of nanoscale samples.

The optical microscopy and spectroscopy labs (Gateway) provides tools to explore the optical properties of nanoscalematerials. This is achieved through high resolution imaging microscopes which measure the optical response of individual nanoscale materials such as carbon nanotubes and a host of nanocrystal structures including dots, rods, and wires. The lab is equipped with a standard inverted optical microscope and a NSOM, which both have cryogenic imaging capabilities. When combined with our variety of excitation and detection systems which range from 400 to 1600 nm and 200 to 1700 nm, respectively, we can investigate a highly diverse range of energetic and temporal photophysical properties of nanoscale materials. In the near future, this capability will be augmented with addition of a magneto cryostat (with fields to 9 Tesla) currently under acquisition. Other capabilities include far-field optical microscopy, single molecule fluorescence detection, time-resolved photoluminescence, atomic force, electrostatic force and scanning current-voltage microscopy. Our capability for time-resolved photoluminescence and photon correlation measurements has been significantly strengthened with recent addition of a pair of superconducting nanowire single photon detectors sensitive to near-IR wavelengths to 1700 nm. Separate capability exists for a dedicated near-IR microscopy, spectroscopy, imaging, and time-resolved PL system optimized for study of single near-IR emitters. Noteworthy is the capability for simultaneous correlated two-color imaging this system provides. It is currently being upgraded to also include back-focal plane imaging capability for characterizing molecular orientations, emission radiation patterns and directivity of optical antennas. Of interest will be probing of strong coupling behaviors between emitters and plasmonic structures and to probe emission pattern control for emitters interacting with new meta- and dielectric structures.

The laboratory for Raman spectroscopy, microscopy, and imaging (Gateway) includes extensive capability for ensemble level and single-nanostructure Raman spectroscopy. Instrumentation includes broadly tunable (UV to near-IR) excitation sources paired to systems for ensemble measurements (tunable from 345 nm to 1000 nm excitation, with fixed instrumentation at 785, 532, 514, and 633 nm). Micro-Raman capability is also available for imaging and single-element spectroscopy, and includes tunable excitation (700-1000 nm exc.) and fixed wavelength (514, 785 nm) confocal microscopy systems. These systems are available for study of a wide range of materials ranging from solutions to bulk solids, thin films, and device structures. As examples, materials studies have included carbon nanomaterials, bio and soft material composites, quantum dots, nanowires, complex oxides, TMDCs, etc.

The chemical synthesis lab (Gateway) enables the design and preparation of optically active semiconductor nanocrystal quantum dots (NQDs), as well as nanoparticles comprising metal oxides, simple metals, and/or magnetic materials. The lab houses six chemical fume hoods, each equipped with a Schlenk line and temperature controllers, and two inert-atmosphere gloveboxes. Laboratory synthetic capabilities include organometallic, inorganic, organic, colloidal and biochemical synthetic methods. Automated fluidic capabilities for synthesis over a wide parameter space of semiconducting quantum dots and heterostructured nanowires are also available. The laboratory also includes capability and expertise for nanoscale integration and self-assembly, including a dip-pen nanolithography system for "writing" semiconducting nanoemitters into assemblies, including onto the active areas of photonic crystal assemblies, cavities, and plasmonic and metamaterial structures. The lab also houses a UV-Vis-NIR spectrometer and a UV-Vis-NIR fluorimeter.

The laboratory for carbon nanomaterials chemistry, processing, and synthesis (Gateway) includes sonication and ultracentrifugation capability for enabling routine generation of carbon nanotube samples in a wide range of matrices, including surfactant suspensions and as sol- and aerogels. Other non-covalent functionalization chemistries are available. Ultracentrifuges and non-covalent chemistries also support expertise and capability in density-based and aqueous two-phase approaches to separations, with single-chirality and electronic-type samples being generated. Expertise is available for studying the fundamentals of non-covalent functionalization aimed at understanding nanotube surface structures and dynamics towards applying that understanding to enhance separations, control photophysical response, enable new self-assembly processes, template 1-D structures, and to enable new optical composite materials. Capability for solution-phase and solid-state methods for low-level covalent functionalization of nanotubes has also been introduced as a new route for enabling emergent optical phenomena. Capability for CVD growth of ultralong, parallel single-walled carbon nanotubes and large area graphene also exists.

The pulsed laser deposition lab (Gateway) enables the epitaxial growth of metal-oxide films, including both simple and complex metal-oxides as well as nanocomposite films and multilayer and superlattice structures. Research involved with this facility includes the growth of complex functional materials with an emphasis on multifunctional nanocomposite metal-oxide films and nanostructured multilayer structures, the use of strain engineering to tune the physical properties of nanoscale metal-oxide films, and the identification of the fundamental mechanisms of the lattice-strain and size effect on the properties of nanoscale metal-oxide films.